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Space Storable Thruster Investigation

by

J. G. CAMPBELL

October 1971

THE MARQUARDT COMPANY
CCI Aerospace Corporation

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3-12058
Steve Cohen, Project Manager

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FINAL REPORT

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by

J. G. Campbell

THE MARQUARDT COMPANY
CCI Aerospace Corporation
Van Nuys, California

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CONTRACT NAS 3-12058

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Cleveland, Ohio
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Liquid Rocket Technology Branch

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FOREWORD

This report was prepared by The Marquardt Company under Contract NAS3-12058, "Space Storable Thruster Investigation". It is the final report on the subject contract. Technical effort began on June 27, 1969, and was completed December 15, 1970.

Contract NAS 3-12058 was administered by the Lewis Research Center, Liquid Rocket Technology Branch, of the National Aeronautics and Space Administration, Cleveland, Ohio. The NASA Project Manager was Mr. Steve Cohen.

The following personnel at Marquardt contributed to the technical effort described in this report: J. G. Campbell and C. D. Coulbert (Program Managers), R. J. Fio Rito (Project Engineer), M. Wilson (Analysis), A. Malek and R. Loustau (Design).

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ABSTRACT

A program of design, analysis and test firing was conducted to study the feasibility of using a radiation and film cooled 25 pound (111.2 newton) thrust graphitic thrust chamber with the liquid cryogenic propellants FLOX/propane and FLOX/methane.

Liquid propane and methane were used as film coolants in the first series of test firings. Carbon deposition on the injector and chamber walls prevented attainment of long run durations over 2 minutes. Less deposition occurred from liquid methane than from liquid propane.

Gaseous methane was used for film cooling in the final series of test firings. Carbon deposition was less severe using gaseous methane cooling than that experienced using liquid methane, but firing duration of a graphite chamber was again limited to 2 minutes because of carbon buildup and erosion of the throat. Data are presented on injector performance, film cooling effectiveness and carbon deposition.

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SPACE STORABLE THRUSTER INVESTIGATION

SECTION I
SUMMARY

A program of design, analysis and test firing was conducted to study the feasibility of using radiation and film cooled graphitic 25 pound (111.2 newton*) thrust rocket engines with the liquid cryogenic propellant combinations FLOX/methane and FLOX/propane.

Film cooling was provided by methane or propane, which also was intended to provide a chemically inert film along the chamber wall to avoid reaction between FLOX and the graphite chamber. The goal of the program was to accumulate a total firing time on one chamber of 1800 seconds with a C* efficiency of 92% and a chamber pressure of 100 psia (68.9 N/cm^2). Nominal mixture ratios of 5.75 for FLOX/methane and 4.5 for FLOX/propane were to be reduced up to 30 percent during test firings. Test firings with existing 100 pound (445 newton*) thrust injectors and chambers were also conducted.

A 6-on-1 injector configuration was designed and fabricated for the 25 pound-thrust testing. Interchangeable film cooling rings of several configurations were designed to adapt to the 6-on-1 injector core, providing rapid change of the amount of film cooling.

Test firings at the 25-pound-thrust level were performed under two separate tasks of the program. In Task IV, 27% and 47% liquid fuel film cooling was used with copper and graphite heat sink chambers over a mixture ratio range from 2.14 to 5.44. The nominal chamber pressure was 100 psia (68.9 N/cm^2). The C* efficiency ranged from 98% to 84%, depending on mixture ratio, percent film cooling and L*. A total of sixty test firings were made with an accumulated firing time of over 1200 seconds.

In Task VI, gaseous methane was used for film cooling the chamber. High engine performance was obtained with up to 76% film cooling. A 120-second test of a graphite chamber was made at a mixture ratio of 3.82 with 76% fuel film cooling.

Accomplishments during the program included the following:

1. Demonstration of high engine performance with C* efficiencies between 90% and 98%, with both gaseous and liquid fuel cooling.

2. Use of instrument grade methane to eliminate hydrocarbon impurities with low pyrolysis temperatures.

* The terms "25-pound-thrust" or "100-pound-thrust" are nominal engine designations and the conversions to 111.2 newtons or 444.8 newtons will not be repeated where the units refer only to the nominal designation.

3. Demonstration of axisymmetric injector propellant distribution with no streaking tendencies.

4. Demonstration of less carbon deposition with gaseous methane cooling than with liquid methane or propane film cooling.

5. Test firing of a POCO graphite thrust chamber for two minutes, while maintaining structural integrity.

Despite these accomplishments, the test firing results lead to the conclusion that carbon deposition still occurs in an amount that precludes attainment of an 1800-second firing capability.

SECTION II
INTRODUCTION

The objective of this program was to demonstrate 1800 seconds steady-state operation of a 25-pound-thrust radiation cooled thruster with the liquid cryogenic propellant combinations FLOX/methane and FLOX/propane. The performance goal was 92% C* efficiency at a chamber pressure of 100 psia (68.9 N/cm^2). The thruster was film cooled by a portion of the fuel.

The design approach was to use a graphite thruster for long duration firings. The walls of the thruster would be protected from chemical erosion and overheating by using a portion of the hydrocarbon fuel for film cooling. The film cooling was injected along the chamber wall near the injector/chamber interface, and passed along the chamber wall toward the throat. Previous experience (Reference 1) with this design approach had shown that one of the major difficulties was the formation of carbon deposits on the chamber wall from the pyrolysis of the fuel. On the other hand, the presence of excess carbon in the thruster boundary layer was desirable to prevent chemical erosion of the graphite chamber by fluorine bearing species of the combustion products. It was expected that a sensitive balance between mixture ratio along the chamber wall and the wall temperature would be required to achieve cooling and chemical film protection of the chamber, and yet avoid carbon deposits. If carbon deposits on the chamber, it would disrupt the film cooling, which would cause overheating and subsequent chemical erosion of the graphite. The throat of the thruster can also be partially blocked by carbon deposits.

A six-on-one single element septad was chosen for the injector core. The primary factors influencing the choice of this core design were: (1) the small orifice area required for the liquid fuel at the 25-pound-thrust level and mixture ratios near 5, and (2) the desire to obtain an axisymmetric injector element to eliminate streaks at high or low mixture ratios. The choice of a six-on-one element was also influenced by 100-pound-thrust test firings early in the program using a like-doublet injector and graphitic thrust chambers available from a previous program (Reference 1). The 100-pound-thrust testing had shown serious carbon deposition problems, and it was thought that a more axisymmetric injector might alleviate the problem of carbon deposits.

A removable film cooling ring was used with the 25-pound-thrust injector core to provide a variety of geometric injection techniques. Comparisons of carbon deposits were obtained between liquid methane and liquid propane cooling, and also between gaseous and liquid methane cooling.

SECTION III
INJECTOR DESIGN AND FABRICATION

A. Injector Design

A design study was made to select the injector configuration best suited to satisfy the following design criteria:

Propellants

1. FLOX/methane at O/F of 5.75
2. FLOX/propane at O/F of 4.5

Vacuum thrust - 25 pounds (111.2 newtons)

Chamber pressure - 100 psia (68.9 N/cm^2)

Expansion ratio - 40:1

Characteristic Velocity Efficiency Goal - 92%

Cooling - fuel film cooling (40% maximum) plus radiation cooling

Other design criteria included the provision of an axisymmetric combustion gas core to eliminate carbon deposition or erosion on the chamber, and attachment of close-coupled valves.

Two basic injector element configurations were considered:

1. An impinging set of 6 oxidizer jets on one fuel jet with 12 fuel film cooling jets.

2. Alternating like-doublets of 5 fuel and 5 oxidizer doublets with 10 fuel film cooling jets.

Studies indicated advantages in favor of the first mentioned configuration (six-on-one) for the following reasons:

1. Ease of fabrication with more precise control of the jet impingement.

2. Better control of propellant distribution to prevent streaking and erosion.

3. Better and more distinct geometrical separation of the core propellant distribution from the boundary layer film which allows better control of boundary layer mixture ratio to investigate its influence on carbon deposition and erosion.

The six oxidizer on one fuel impinging jet configuration was expected to produce a uniform oxidizing region in contact with the fuel film at the chamber boundary layer which would react to prevent free carbon deposition.

A review of Marquardt and industry experience with Septad-type injector elements indicated that satisfactory combustion performance could be achieved with the hypergolic FLOX/LPG type propellants. A new feature was also incorporated into the design which allowed the film cooling ring to be constructed and interchanged independently from the main injector core for more detailed investigation of the film injection parameter influence upon both erosion and carbon deposition.

A schematic diagram of the injector core geometry and the film cooling ring is shown in Figure 1.

B. <u>Injector Fabrication</u>

Two injectors were fabricated with the basic core design shown in Figure 1. The nominal design point of the injectors was at a mixture ratio of 5.0 with 30% fuel film cooling, resulting in a core mixture ratio of 7.15. The impingement angle of the six oxidizer orifices was 30 degrees. The core material was Nickel 200. The design parameters of the two injectors are summarized in Table I and discussed below.

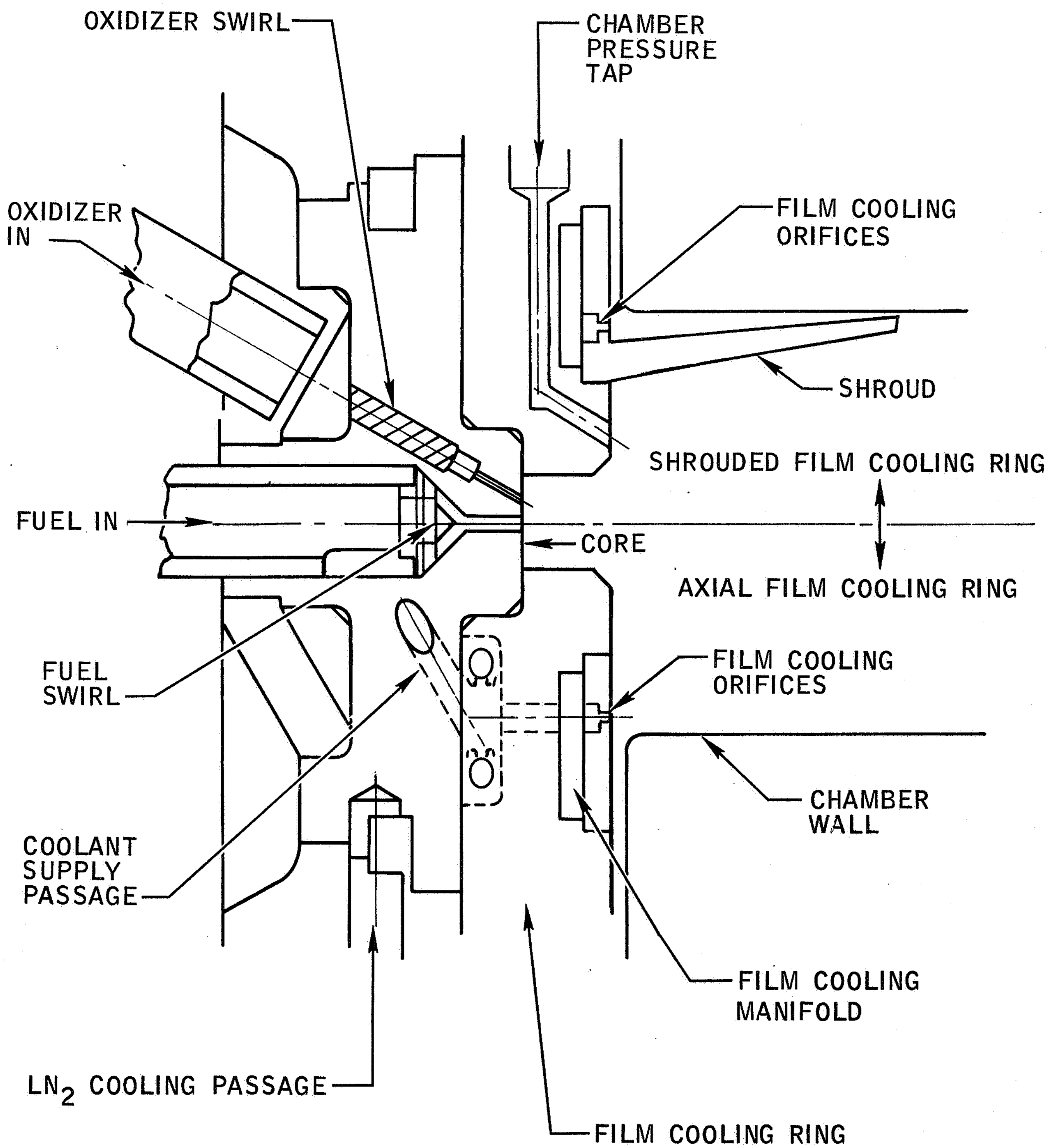

Figure 1. - Injector Core and Film Cooling Ring Assembly
Task IV - February 1970

TABLE I

DESIGN PARAMETERS OF INJECTOR CORE

O/F = 5.0 30% FILM COOLING

FLOX/METHANE

α Impingement Angle Deg.	Oxidizer Jet Diameter D_o	Fuel Jet Diameter D_f	$\frac{D_f}{D_o}$	Momentum Ratio $\frac{\dot{W}_f V_f}{\dot{W}_o V_o}$	Mixture Ratio O/F Core	Fuel Swirl	Oxidizer Swirl
30	.0139 in. (.0353) cm.	.0174 in. (.0442) cm.	1.25	.259	7.15	Yes	Yes

S/N 001 Injector Core

The S/N 001 injector core had six 0.0139 inch (.0353 cm) diameter oxidizer orifices impinging at a 30 degree angle on one axial fuel orifice. An oxidizer swirl was created through the grooves of a No. 62 high speed, high helix steel drill section which was inserted in the entrance to each oxidizer orifice. The drill section was 0.200 inch (0.508 cm) long and was coated with electroless nickel.

The fuel orifice had a diameter of 0.0174 inch (0.0442 cm) and had an entrance swirl of the type shown in Figure 2.

S/N 002 Injector Core

The S/N 002 injector core was identical to the S/N 001 injector core except that an 0.025 inch (0.0635 cm) diameter counterbore to a depth of 0.030 inch (0.0762 cm) was added to the exit of each oxidizer orifice. Water flow testing showed that the resultant expansion of the oxidizer streams caused an expanding spray pattern which was predicted to give better engine performance.

C. Film Cooling Rings

Two film cooling ring configurations as shown schematically in Figure 1 were used. The film cooling ring was made of Nickel 200. The fuel film cooling entered the film cooling ring through an orifice connected to the core fuel manifold. The fuel coolant passed through a distribution manifold in the film cooling ring and then entered the chamber through axially flowing orifices on a basic diameter of 0.650 inch (1.65 cm).

Axial Flow Film Cooling Ring

The axial flow film cooling ring shown in the lower half of Figure 1 was designed to pass 30% of the fuel through 12 evenly spaced 0.003 inch (0.00762 cm) diameter orifices flowing parallel to the chamber wall, which had an ID of 0.712 inch (1.81 cm). Therefore, the cooling jets were about 0.031 inch (0.0788 cm) from the wall.

Shrouded Film Cooling Ring

The shrouded film cooling ring, shown schematically in the top half of Figure 1, differed from the axial flow film cooling ring only in the addition of a shroud which extended about 1/2 inch (1.27 cm) into the combustion chamber. The film cooling jets impinged on the back of the shroud and passed through a thin gap of about 0.010 inch (0.0254 cm) between the chamber wall and the tip of the shroud. It was expected that the equilibrium length of the shroud would be somewhat less than 1/2 inch (1.27 cm) and would be determined empirically during the first test firings.

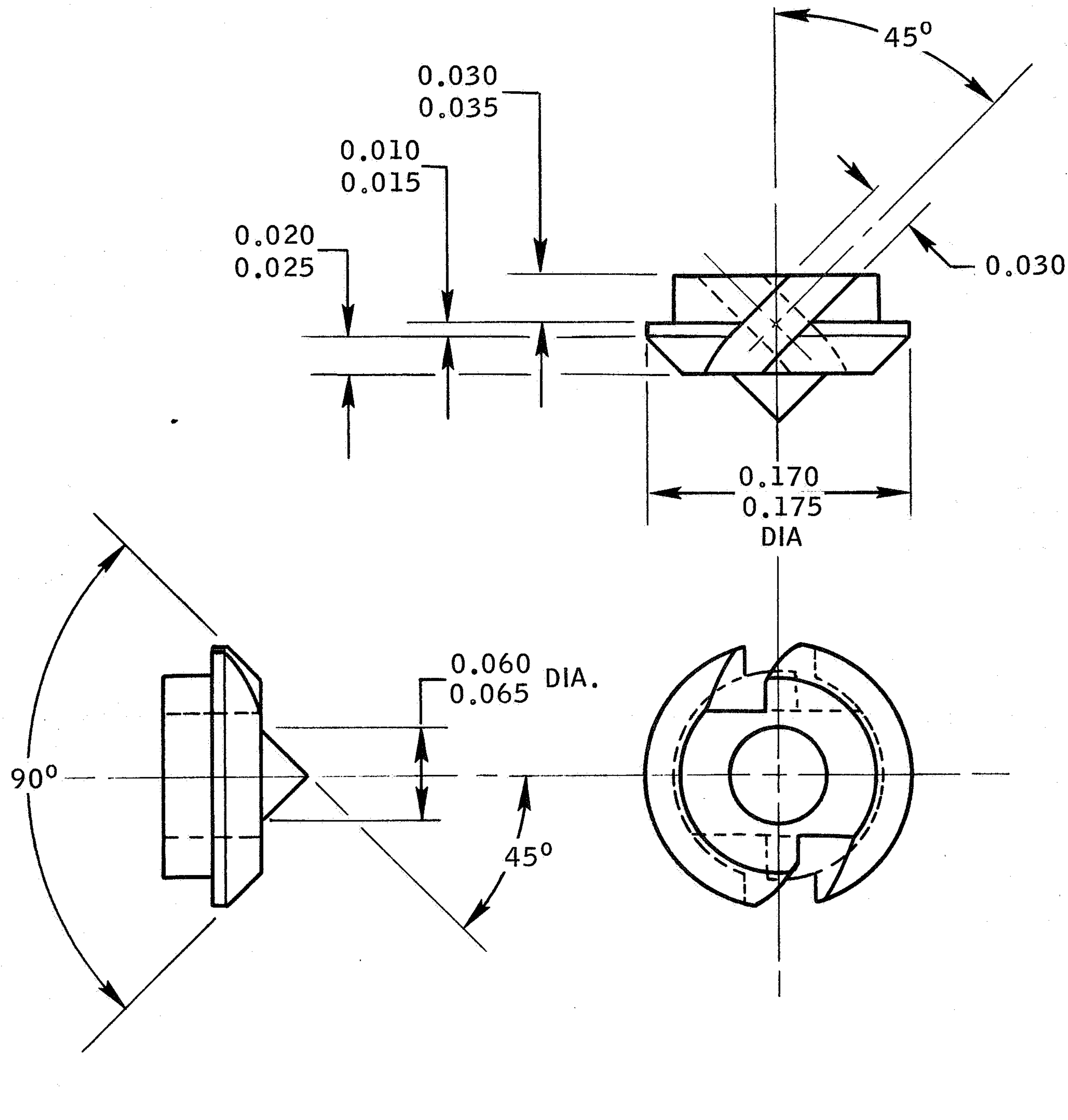

Figure 2. - Fuel Swirl Design

D. Injector Propellant Distribution Tests

A series of cold flow tests were made on both injector core configurations at flow rates corresponding to three different propellant mixture ratios. Tests were conducted with trichlorethylene and water to simulate oxidizer and fuel, respectively. The results of the tests are shown in Figure 3, which gives the mixing factor (E_m) as a function of the mixture ratio. The mixture ratio shown in the graph has been converted from the trichlorethylene/water simulants to FLOX/methane. The S/N 001 core was tested with the axial flow film cooling ring, and the S/N 002 core was tested with the shrouded film cooling ring.

It is seen from the results of the E_m evaluation that injector S/N 002 shows a higher mixing factor characteristic than S/N 001. This is attributed to the modification which was made to injector S/N 002, which distinguishes it from S/N 001. This modification consists of a 0.025 inch (0.0635 cm) diameter counterbore to the six oxidizer injection orifices, which reduces the length of the 0.0134 inch (0.034 cm) diameter oxidizer injection orifice. This reduction in flow passage length allows the induced swirl at the oxidizer orifice inlets to be more predominant in the discharge spray pattern and this enhances mixing. The effect of the counterbore is also quantitatively demonstrated in the comparison charts of Figures 4 and 5. Figure 4 shows the results of Run No. 6 for injector S/N 001 and presents the distribution of mass of propellants and mixture ratio for each of the collector tubes in the bifluid spray collector matrix. Figure 5 shows a similar data listing for Run No. 13 and injector S/N 002. It is seen that the effect of the counterbore also results in spreading the mass distribution of the spray over the cross-sectional area of the collector matrix. A photograph of the bifluid flow test booth is shown in Figure 6. The injector is installed over the spray collector matrix of 49 tubes which was modified from the collector used in previous testing (Reference 1) by fabrication of a new brazed 7 x 7 square assembly of 49 tubes (3/16 inch) (0.476 cm) with the top of the matrix flat with a very close tolerance. A 2-inch (5.08 cm) length of chamber section is attached to the injector discharge to simulate the effect of the chamber confining walls on the spray pattern. The discharge of the chamber section is located three inches (7.62 cm) above the collector matrix. Figure 7 is a photograph of the injector water calibration test showing the water spray pattern for both fuel and oxidizer of the S/N 001 injector. Figure 8 is a photograph for the same water flow conditions of injector S/N 002. It is noted that the spray pattern for S/N 002 injector with the counterbore oxidizer holes is more diffuse than that for S/N 001. The S/N 002 injector configuration includes the fuel film injector ring having a circumferential baffle to vaporize and distribute the fuel film at the chamber boundary layer. The water flow calibration data indicated a measured film injection rate of 28% of the total fuel flow for S/N 001 and 30% for S/N 002 injector.

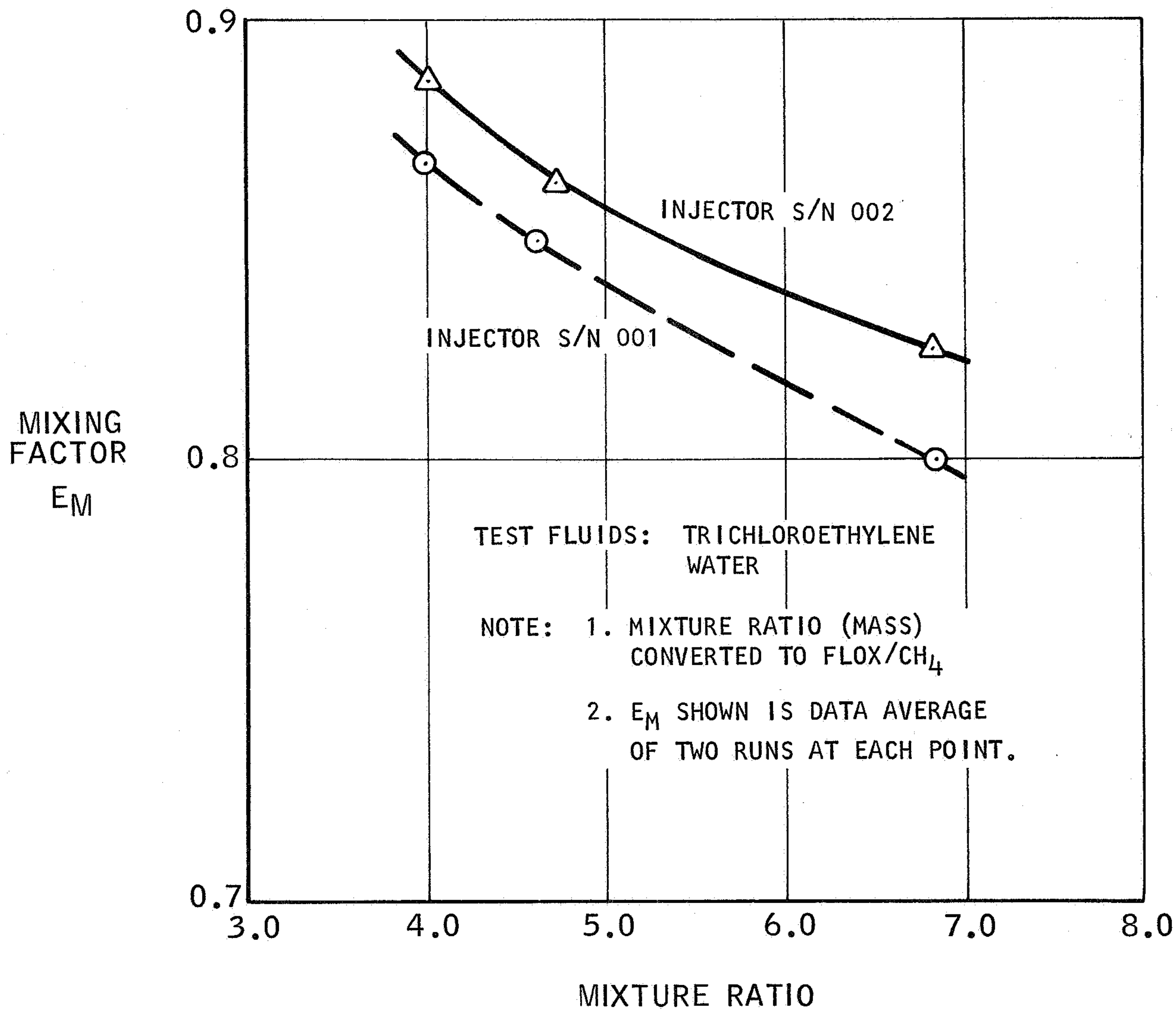

Figure 3. - Injector Bifluid Flow Characteristics

COLUMNS

ROWS	1	2	3	4	5	6	7
1	0 35 —	0 36 —	0 34 —	0 32 —	0 30 —	0 25 —	0 24 —
2	0 40 —	0 38 —	0.85 35 0	0 31 —	0.85 27 0	0 23 —	0 22 —
3	0 42 —	4.13 39 2.24	13.33 33 2.3	26.9 29 3.36	4.35 26 1.92	1.06 20 0	0 21 —
4	0 43 —	7.42 44 3.36	49.62 41 5.67	40.81 28 3.36	19.68 18 3.36	3.21 17 2.02	0 19 —
5	0 46 —	4.85 47 2.80	26.05 45 3.9	37.10 8 3.73	30.41 11 5.51	3.5 15 4.49	0 16 —
6	0 48 —	0 1 —	2.07 3 2.24	4.85 5 2.8	6.07 10 4.71	0 12 —	0 14 —
7	0 49 —	0 2 —	0 4 —	0 6 —	0 7 —	0 9 —	0 13 —

TOTAL VOLUME ml

TUBE NO.

O/F ($FLOX/CH_4$)

Figure 4. - Injector S/N 001 Cold Flow Distribution for Run 6
Overall FLOX/Methane O/F = 4.0

COLUMNS

ROWS	1	2	3	4	5	6	7
1	0 37 —	0 36 —	1.85 34 3.36	0.85 32 0	0 30 —	0 25 —	0 24 —
2	0.85 40 0	3.92 38 2.69	9.78 35 4.11	10.28 31 5.05	5.27 27 2.10	1.85 23 3.36	0 22 —
3	3.63 47 1.44	14.12 39 3.15	28.48 33 4.83	38.84 29 5.53	22.76 26 3.66	8.77 20 2.75	0.85 21 0
4	5.99 43 2.52	30.43 44 2.99	40.54 41 4.3	39.40 28 4.45	43.61 18 4.55	19.48 17 3.36	0 19 —
5	6.49 46 3.36	33.47 47 3.77	37.68 45 3.93	25.76 8 3.47	26.47 11 3.61	10.41 15 3.08	0.85 16 0
6	2.28 48 1.68	9.78 1 4.11	18.63 3 4.16	9.70 5 2.80	4.13 10 2.24	1.06 12 0	0 14 —
7	0 49 —	1.85 2 3.36	1.85 4 3.36	1.85 6 3.56	0 7 —	0 9 —	0 13 —

TOTAL VOLUME ml

TUBE NO.

O/F ($FLOX/CH_4$)

Figure 5. - Injector S/N 002 Cold Flow Distribution for Run 13

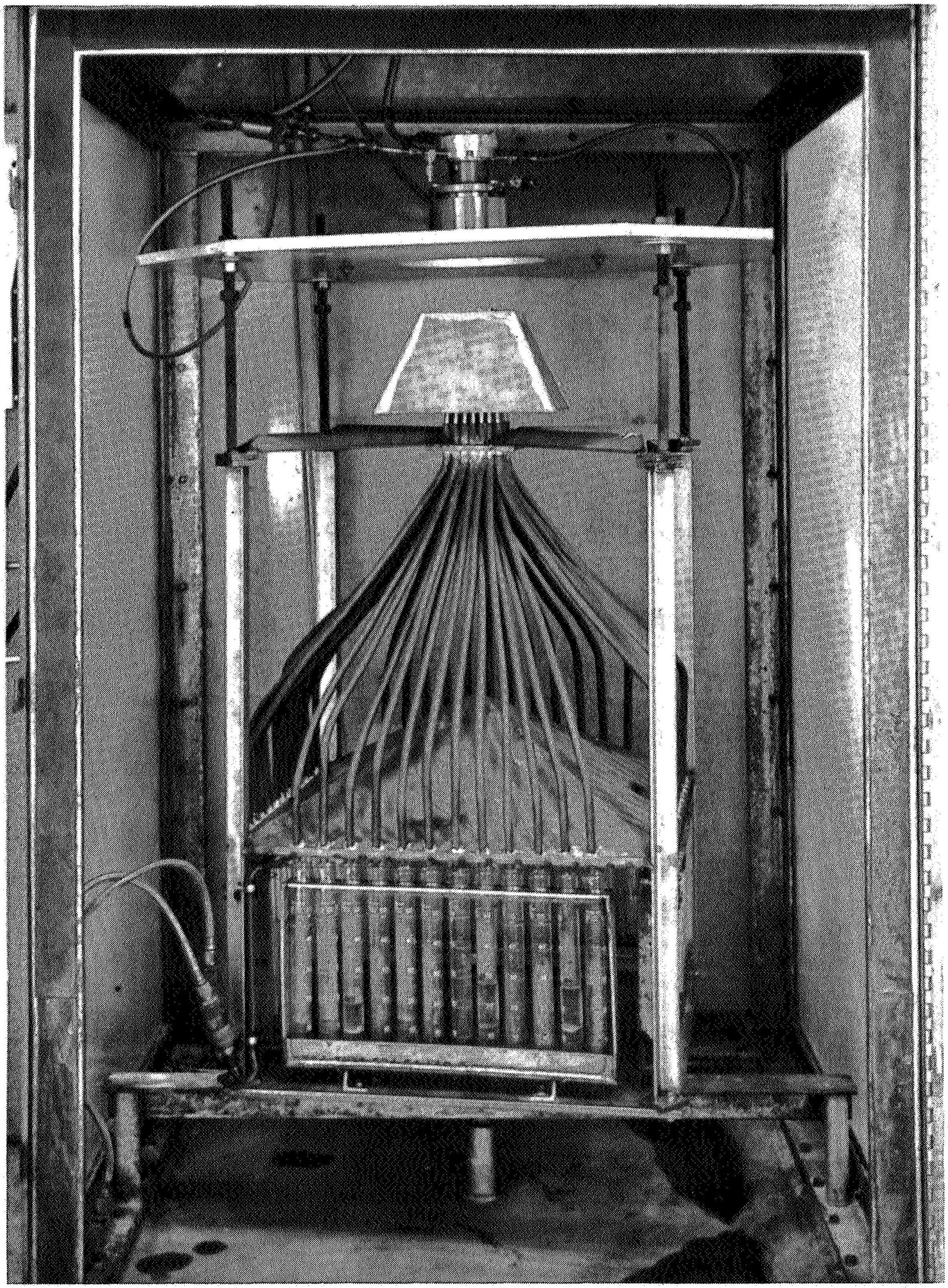

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Figure 6. - Spray Booth Used for Bifluid Flow Test of Injector

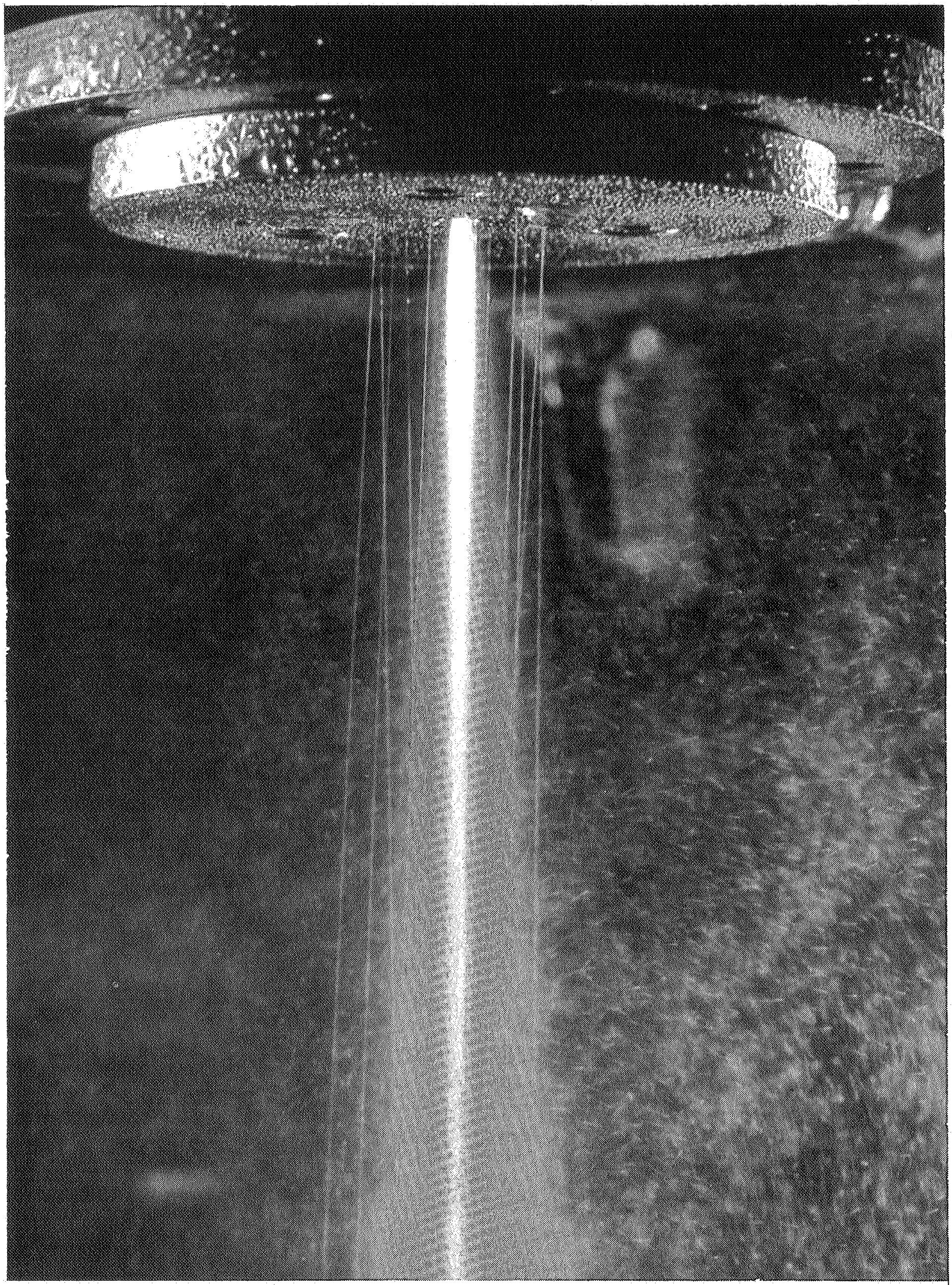

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Figure 7. - Water Spray Pattern - S/N 001 Injector

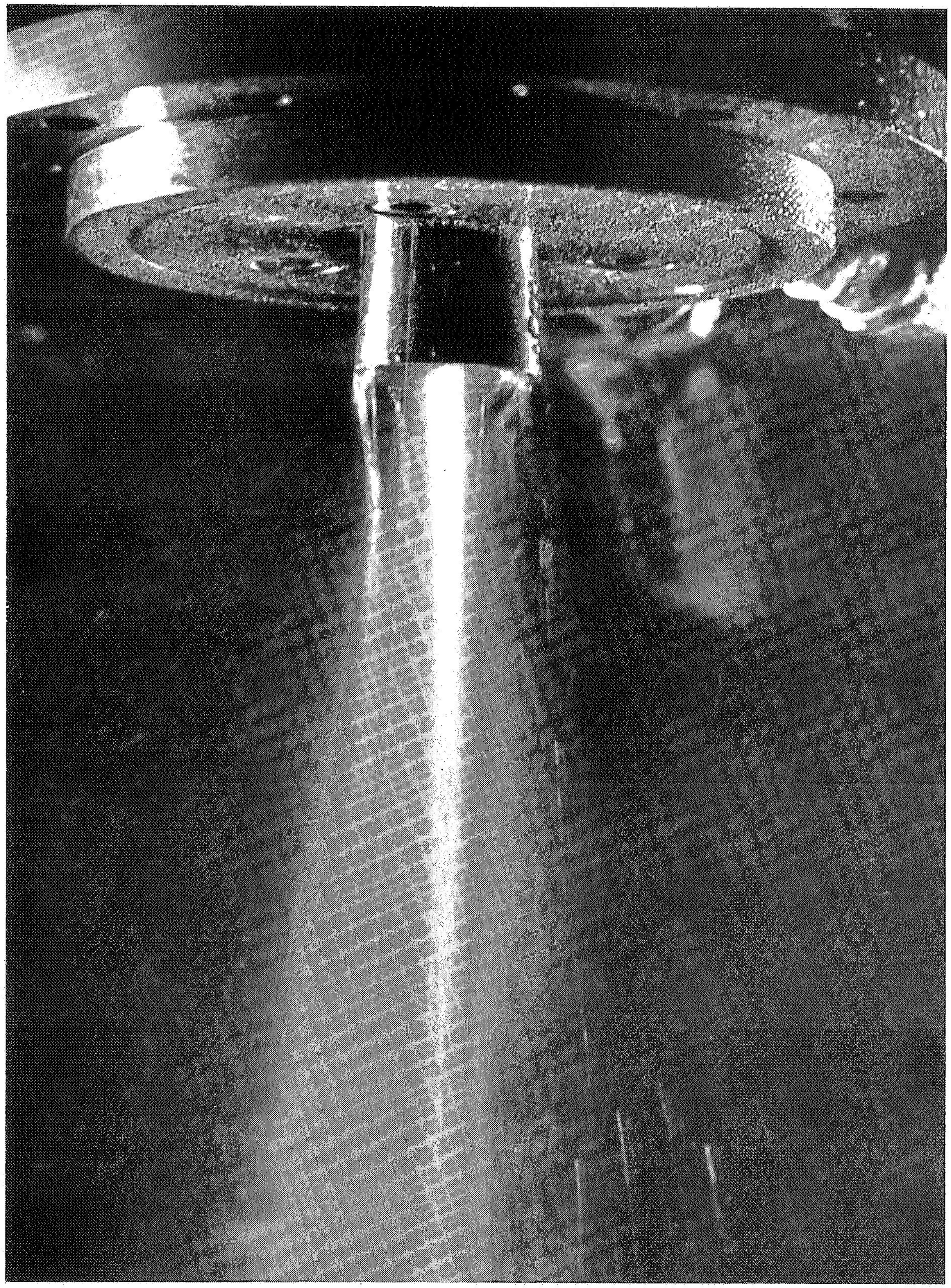

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Figure 8. - Water Spray Pattern - S/N 002 Injector

SECTION IV
THRUST CHAMBER DESIGN AND FABRICATION

A. 25-Pound Thrust Engine for Task IV Testing

Copper heat sink chambers were used for Task IV test firings at the 25-pound thrust level to determine engine performance. POCO graphite chambers were used in long duration firings. Injector streaking tendencies were determined by using replaceable sleeves of Pyrolarex 300 or pyrolytic graphite inside the combustion chamber adjacent to the injector.

Both the copper and POCO graphite chambers were of the same configuration and were assembled to the injector as shown in Figure 9. Copper chambers were fabricated in two lengths - 2.5 inches (6.35 cm)/(L* = 7 inches) (17.8 cm) and 4 inches (10.16 cm)/(L* = 11 inches) (28 cm), from the injector face to the throat. Thermocouples were installed at the throat of the copper chamber a distance of about 0.30 inches (0.762 cm) from the inner surface. The copper chambers were made of oxygen-free high conductivity copper.

Two graphite chambers with a length of 4 inches (10.16 cm) and two with a length of 6 inches (15.25 cm) were fabricated from AXF-5Q POCO graphite. A Pyrolarex 300 sleeve was inserted in one POCO chamber of each length. The four POCO chambers are shown before final machining of the Pyrolarex sleeves in Figure 10.

For some tests of Task IV testing, a pyrolytic graphite sleeve was used instead of a Pyrolarex sleeve. The wall thickness of the pyrolytic graphite sleeve was 0.040 inch (0.1016 cm), the length 2 inches (5.08 cm), and the I.D. of the sleeve was 0.880 inch (2.23 cm), compared to 0.717 inch (1.82 cm) for the Pyrolarex sleeve.

B. 25-Pound Thrust Engine for Task VI Testing

The combustion chamber assemblies for Task VI testing (shown in Figure 11) differed from those used in Task IV. A gas film cooling adapter was designed in Task VI to inject gaseous methane at 70°F through a 0.003-inch (0.00762 cm) slot parallel to the chamber wall. The 0.003-inch (0.00762 cm) gap was intended to provide matching velocity of the combustion gas core and the film for optimized film cooling by a film flow rate of 0.0075 lb/sec (0.0034 kg/sec). This film cooling flow rate corresponded to 60% film cooling at a mixture ratio of 4.5. The film cooling ring was replaced by a water cooled ring, as shown in Figure 11. The chamber I.D. was increased to 1.330-inches (3.38 cm) (a contraction ratio of 10:1) to decrease the total heat flux to the chamber wall.

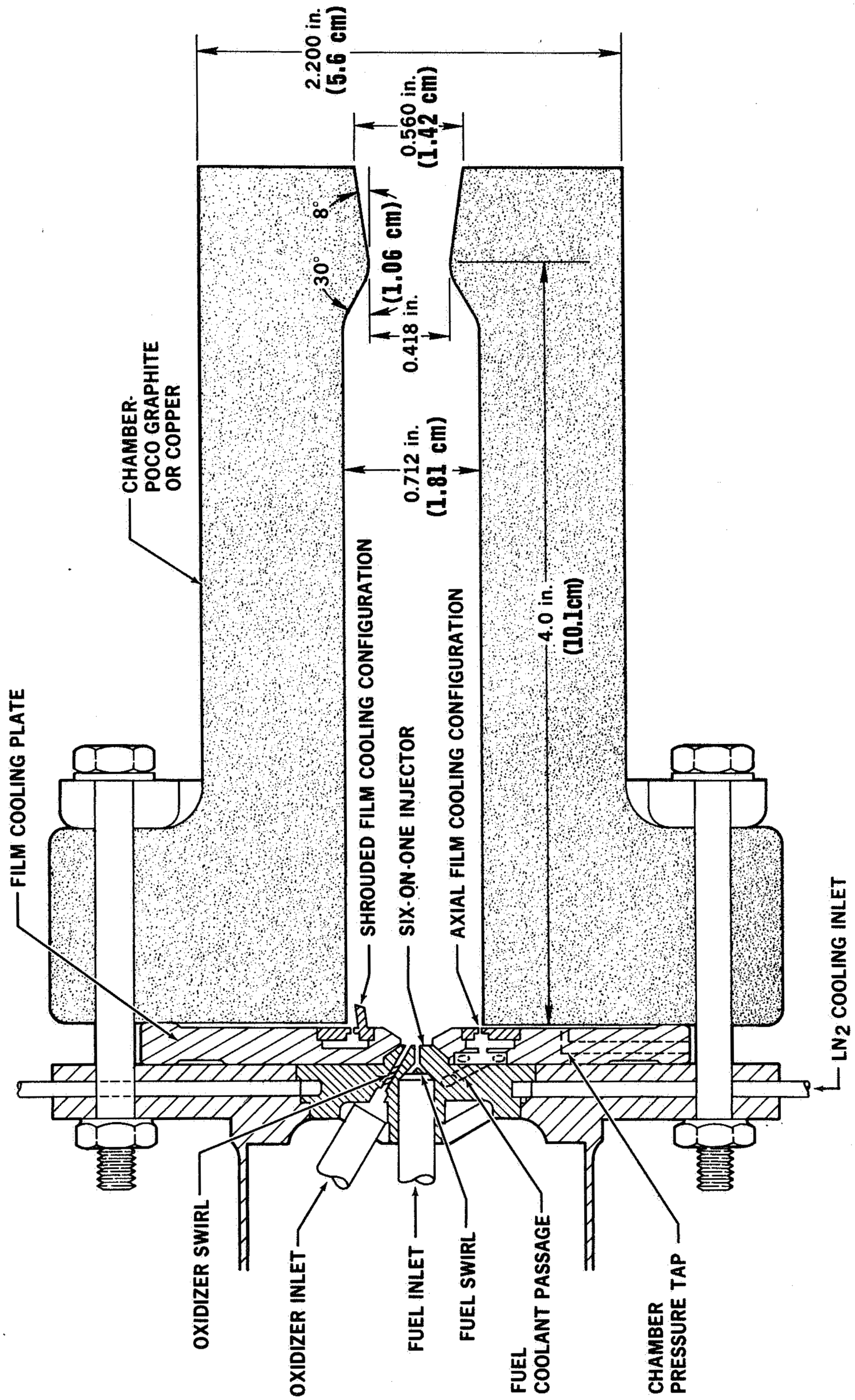

Figure 9. - 25-Pound FLOX/LPG Engine Assembly - Task IV Tests
Liquid Film Cooling

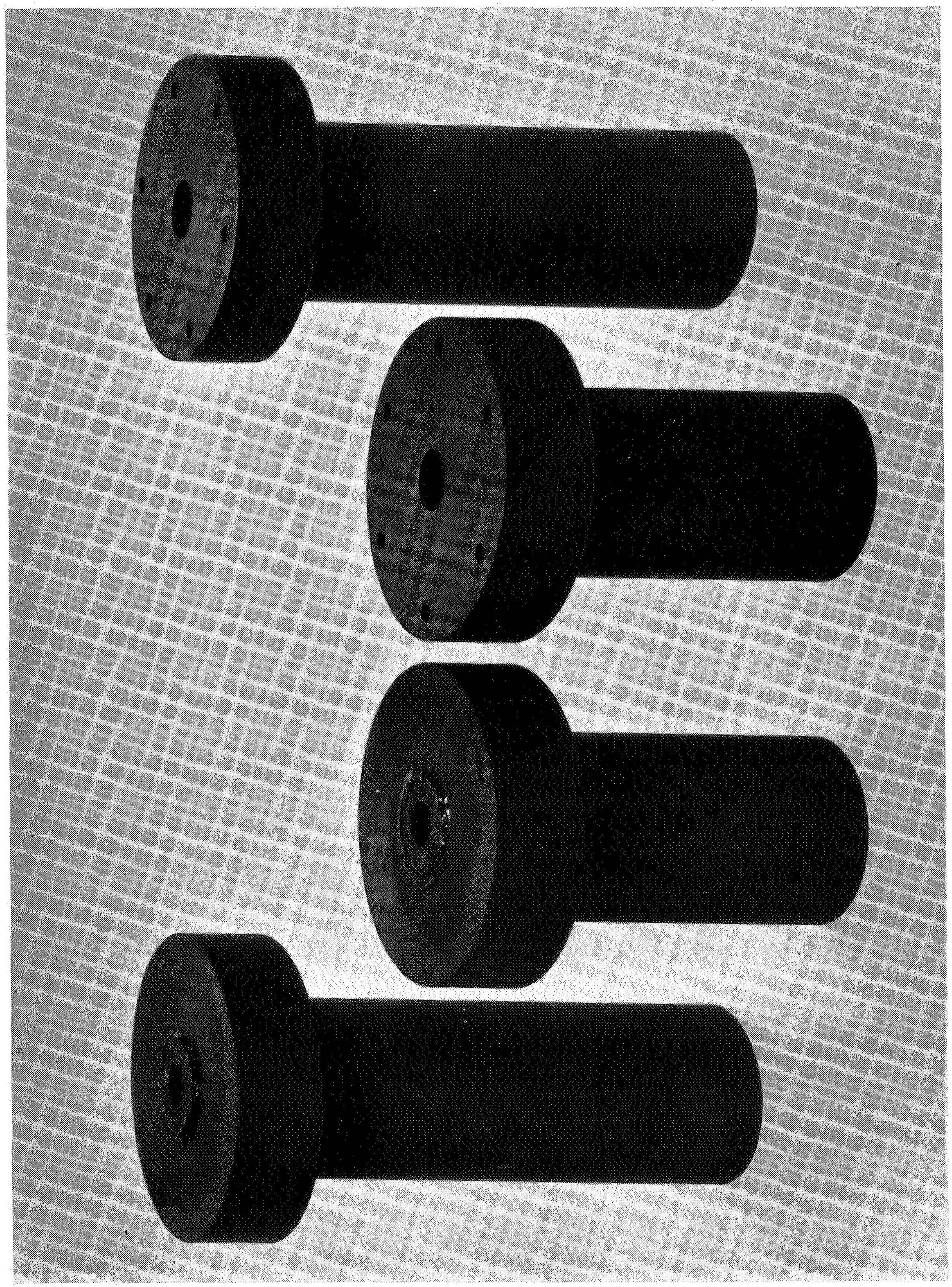

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Figure 10. - POCO Graphite Chambers for Task IV Testing

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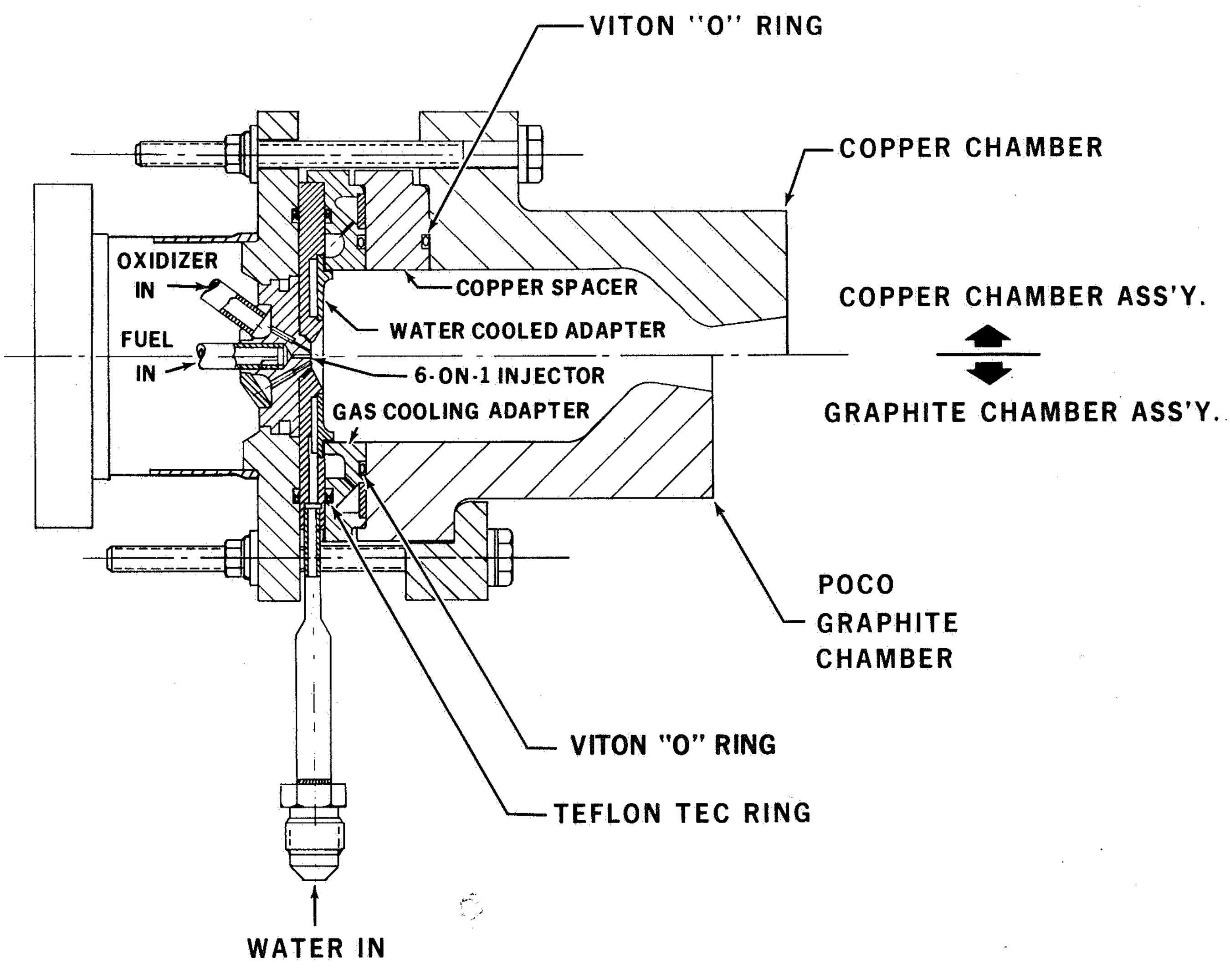


Figure 11. - 25-Pound Thrust FLOX/Methane Engine Assembly for Task VI Tests
Gas Film Cooling

The combined length of the gas film cooling adapter, plus a short copper chamber, was 2.5-inches (6.35 cm) (L* = 21 inches) (53.4 cm). Three copper chamber sections were also fabricated in lengths of 1/2-inch (1.27 cm), so that one or more sections could be added to the copper chamber assembly in the manner shown in the top half of Figure 11 to give chamber lengths (from injector to throat) of 2.5, 3.0, 3.5 or 4.0 inches (6.35, 7.62, 8.9 or 10.16 cm).

The POCO graphite chamber design used in Task VI testing is shown in Figure 11. The O.D. of the attach flange was reduced from that used in Task IV testing to eliminate the stress concentration near the bolt holes. POCO AXF-5Q chambers were fabricated in lengths which, combined with the gas cooling adapter, yielded chamber lengths of 2.5, 3.0 and 3.5 inches (6.35, 7.62 and 8.9 cm).

SECTION V
TEST FIRINGS OF 100-POUND-THRUST CHAMBERS

Thrust chambers and injectors available from a previous contract (Reference 1) were tested with FLOX/methane at the 100-pound-thrust level. The injectors were like-doublet injectors and are described in Reference 1. The injectors had a conical shoulder for attachment of the chambers as shown in Figure 12. The injector face of the S/N 002 100-pound-thrust injector is shown in Figure 13. The large doublets are for FLOX; the central hole is a chamber pressure top.

Test firings were conducted at the same time as test firings under contract NAS7-555 which are reported in Reference 2.

A run and data summary is shown in Table II. The testing involved two injectors and 10 chambers of various materials and configurations including:

1. POCO graphite No. 1, L* = 14 in. (35.5 cm)
2. POCO graphite No. 2, L* = 10 in. (25.4 cm)
3. PG/Thornel/Resin composite No. 1, L* = 14 in. (35.5 cm)
4. PG/Thornel/Resin composite No. 2, L* = 14 in. (35.5 cm)
5. PG/Carbitex composite SL-1, L* = 14 in. (35.5 cm)
6. POCO graphite No. 3, L* = 14 in. (35.5 cm)
7. PG/Thornel/PG No. 1, L* = 14 in. (35.5 cm)

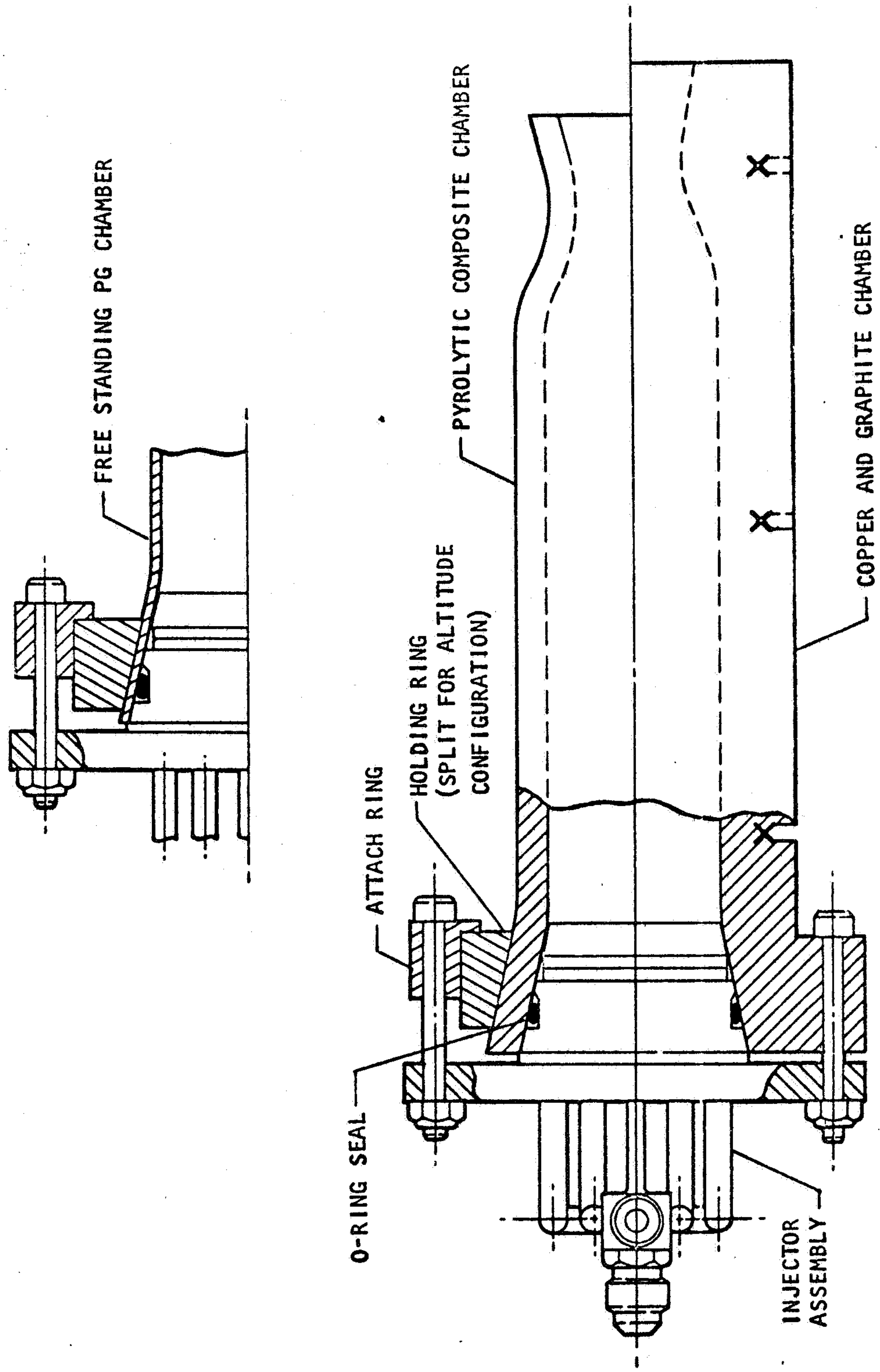
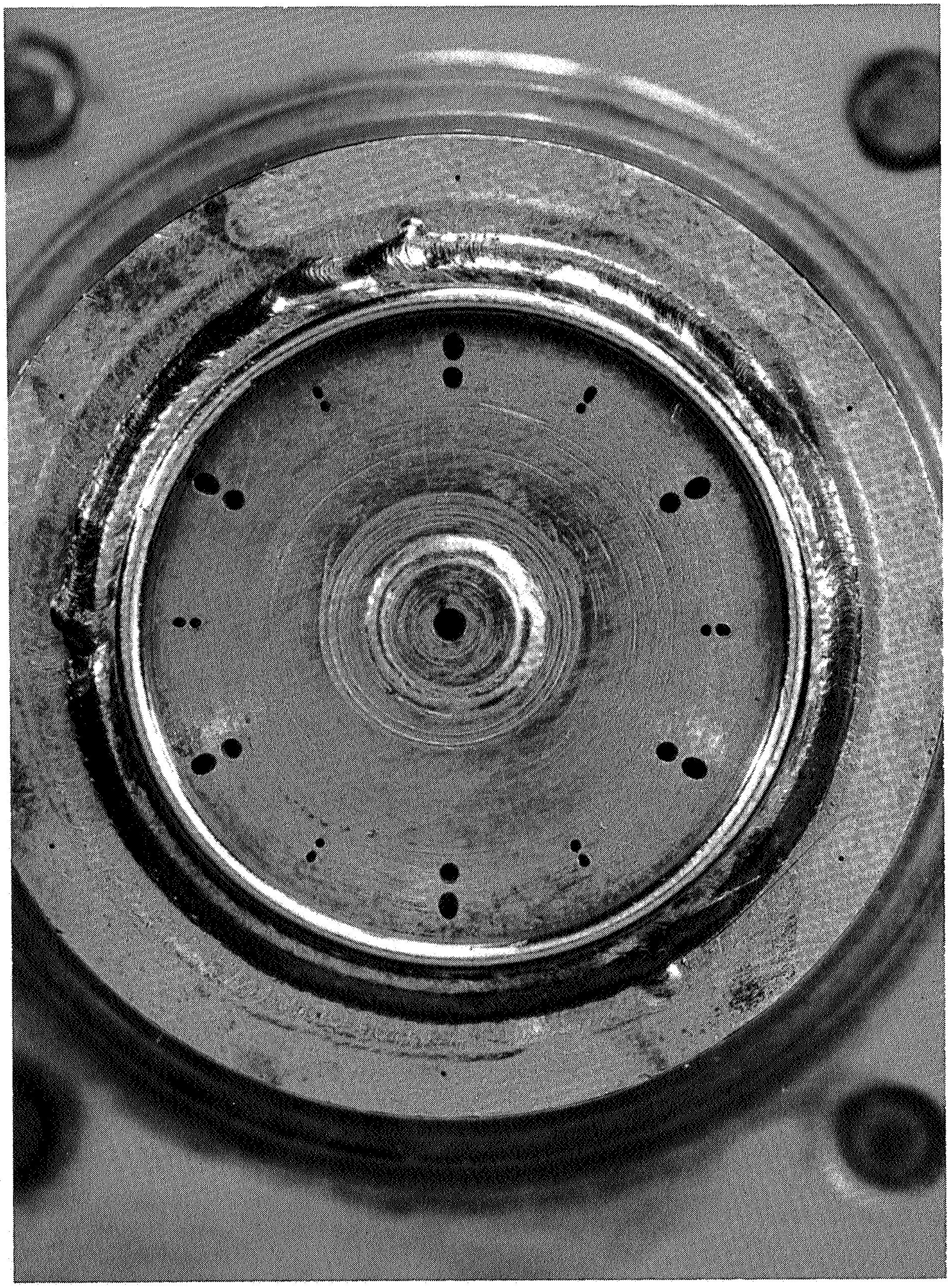


Figure 12. - 100-Pound Thrust Engine Assembly



NEG. 9470-3

Figure 13. - 100 Pound Thrust Injector S/N 002

TABLE II

TEST FIRING SUMMARY - TASK VII - 100 POUND-THRUST ENGINE
FLOX/METHANE

RUN NO.	DATE	CONFIGURATION CHAMBER	CONFIGURATION INJECTOR	RUN DURATION SEC	THROAT EROSION RATE MILS/SEC (cm/SEC)	MIXTURE RATIO	CHAMBER PRESSURE PSIA(N/cm^2)	C* FT/SEC (m/SEC)	C* EFF. %	REMARKS
1	7/9/69	Poco No. 1 L* = 14 in. (35.5 cm)	S/N 001	20	N.A.	4.40	110.4 (76.0)	6651 (2030)	96.7	Performance and facility check. Throat carbon deposits.
2	7/9/69	"	"	23	0.15 (0.00038)	4.30	107.4 74.	6631 2020	96.6	Repeat Run 1 Oxidizer flow decay.
3	7/9/69	"	"	26.1	N.A.	4.39	106.4 73.5	6593 (2010)	95.9	P_c increase. Heavy throat deposits.
4	7/10/69	Poco No. 2 L* = 10 in. (25.4 cm)	S/N 002	10	N.A.	- -	- -	- -	- -	Oxidizer leak at injector plate. Data invalid. Throat deposits.
5	7/11/69	PG/TH/resin No. 1	S/N 001	20	0.067 (0.00017)	6.72	77.4 (53.2)	6319 (1925)	94.4	O/F Survey
6	7/11/69	"	"	10		- -	- -	- -	- -	P_c monitor inoperative
7	7/11/69	"	"	20		8.66	52.4 (36.0)	4520 (1379)	73.0	High O/F due to fuel freezing. Transient data.
8	7/11/69	"	"	60.1		4.20	82.4 (56.6)	6804 (2075)	99.7	Duration run. P_c steady.
9	7/11/69	PG/TH/resin No. 2	S/N 001	82	0.14 (0.00035)	4.58	96.4 (66.4)	6765 (6065)	98.2	Duration run. P_c increased.
10	7/15/69	Poco No. 2 L* = 10 in. (25.4 cm)	S/N 002	5		- -	- -	- -	- -	Oxidizer leak at injector plate. Run terminated. Slight throat deposit.
11	7/16/69	PG/Carbitex SL-1	S/N 001	40	0	6.00	100.4 (69.1)	7190 (2190)	104	O/F variation due to oxidizer two phasing
12	7/16/69	"	"	105	0.15 (0.00038)	5.20	85.4 (59.0)	6681 (2038)	96	Duration run. P_c increased then dropped back to nominal

TABLE II (Continued)

TEST FIRING SUMMARY - TASK VII - 100 POUND-THRUST ENGINE
FLOX/METHANE

RUN NO.	DATE	CONFIGURATION CHAMBER	CONFIGURATION INJECTOR	RUN DURATION SEC	THROAT EROSION RATE MILS/SEC (cm/SEC)	MIXTURE RATIO	CHAMBER PRESSURE PSIA(N/cm^2)	C* FT/SEC (m/SEC)	C* EFF. %	REMARKS
13	7/16/69	Poco No. 2 L* = 10 in. (25.4 cm)	S/N 001	30	0.28 (0.00071)	5.62	83.4 (57.4)	5739 (1750)	83.1	O/F - Deposition survey
14	7/16/69	"	"	30	0.12 (0.00030)	5.69	80.4 (55.3)	5627 (1715)	81.7	Repeat Run 13
15	7/16/69	Poco No. 2 L* = 10 in. (25.4 cm)	S/N 001	60	0.32 (0.00081)	4.98	66.4 (45.7)	5949 (1813)	86.1	O/F survey
16	7/18/69	Carbitex SL-2	S/N 002	7	1.14 (0.00290)	- -	- -	- -	- -	Oxidizer leak at injector plate. Run terminated.
17	7/23/69	"	"	20	0.04 (0.00010)	5.67	52.4 (36.1)	4631 (1410)	67.6	Injector fuel/oxidizer momentum angle change performance check
18	7/23/69	"	"	15	0	- -	- -	- -	- -	Run aborted due to photographic difficulty
19	7/23/69	"	"	61	0.41 (0.00100)	5.62	52.4 (36.1)	5006 (1525)	73.0	Minor throat deposits.
20	7/23/69	Poco No. 3 L* = 14 in. (35.5 cm)	S/N 002	20	0	4.54	72.4 (50.0)	4483 (1365)	65.4	Injector performance check. Deep erosion streak in throat.
21	7/23/69	"	S/N 001	60	0.22 (0.00056)	6.2	101.2 (69.7)	6873 2095	100.0	O/F deposition
25	7/25/69	PG/TH/PG No. 1	S/N 002	20	0.06 (0.00015)	6.0	87.4 (60.2)	6004 (1830)	87.6	Injector fuel/oxidizer momentum angle change performance check.
26	7/25/69	"	"	45	0.18 (0.00046)	5.97	89.4 (61.5)	6101 (1860)	88.9	Same

POCO graphite is a fine grained graphite with a particle size of about 0.001 inch. It has higher strength than other commercial graphites, with a tensile strength near 8000 psi. Grade AXF-5Q was used for the thrust chambers.

The PG/Thornel/Resin composite chambers were made by filament winding Thornel-50 around a free standing PG chamber, followed by impregnation of the filament winding with PBI (Polybenzimidazole). The wall thickness of the free standing PG, obtained from Super Temp Co., was 0.050 inch. The filament winding to a thickness of about 0.200 inch and subsequent resin impregnation were done by the Whittaker Corporation.

The PG/Thornel/PG chamber was made in the same way as the PG/Thornel/Resin chambers except that CVD carbon infiltration of the Thornel-50 filaments was used instead of resin for filament bonding.

The two injectors included X22401, S/N 001 which remained identical in configuration as for the Reference 1 program; e.g., 6 fuel, 6 oxidizer like-doublets with injector face deflector ring, 35% film injection and unmodified for bipropellant valve installation.

Injector X24401, S/N 002 had been modified for bipropellant valve installation, but was used with a blank plate instead of the valve for this test series. As indicated by the run summary of Table II, some difficulty was encountered with oxidizer leakage at the blank plate injector interface. The leakage was caused by distortion of the plate which did not occur for the actual valve installation. The difficulty was rectified by welding sealing diaphragms at the plate interface.

The S/N 002 injector was utilized in evaluating the effect of relative stream momentum angle between the oxidizer and fuel doublets. By turning the oxidizer doublet stream momentum inwards relative to the fuel, it was felt that cooling and non-erosion effects could be enhanced. The injector was designed initially for an oxidizer/fuel stream momentum differential of 1 degree. This configuration produced C* efficiencies of approximately 95% during the Reference 1 program. For Runs 17 through 19 the relative momentum differential was changed to 12 degrees and C* performance was seriously affected, dropping to approximately 70%.

For Runs 25 and 26 the momentum differential was reduced to 5 degrees and C* performance improved to approximately 88%. It also appeared that erosion characteristics improved.

Figure 14 is a plot showing the effect of the relative momentum angle change between the fuel and oxidizer doublets on injector C* performance. It is seen that for edge impinging like-doublet injectors, the relative momentum angle change produces a significant effect on mixing and C* performance. It was also noted that considerably less carbon deposition occurred during the high differential momentum angle runs.

A. Graphitic Chamber Evaluation

The results of the test firing evaluation of various graphitic thrust chambers are discussed below:

1. POCO Graphite

Three AXF-5Q POCO graphite chambers were test fired for durations up to 60 seconds. Despite relatively slow heating time because of the heat sink effect, the throat erosion was as much as 0.32 mils/sec (0.00081 cm/sec) (Run 15). The POCO oxidized on the outer surface during the longer runs, and it was noticed during post fire proof tests that the porosity was increased by the firings.

2. PG/Thornel/Resin Composite

Of the two PG/Thornel/Resin composite chambers tested, good erosion data was obtained on Run 9 of 82 seconds duration. The erosion rate (Table II) was 0.14 mils/sec (0.00035 cm/sec) which is a typical value for pyrolytic graphite. The outer wrap was depleted by oxidation from the atmosphere during the test firings, with the residue having the appearance of loose Thornel. It was concluded that the Thornel/Resin reinforcement did not offer any advantages over free standing pyrolytic graphite for the test conditions involved.

3. PG/Thornel/PG Composite

The PG/Thornel/PG chamber was trimmed and pressure checked to 200 psig (137.88 N/cm^2). However, in mounting the chamber on the injector with the tapered seal attachment, the clamping load caused a crack in the PG liner at the attach flare. To allow the test firing to proceed, a sealing compound was used to fill the crack in the liner flare and the test firing was accomplished satisfactorily. During the 65 seconds of firing (Runs 25, 26) a small hole was eroded in the side of the chamber through both the PG liner and Thornel overwrap. No crack or further failure was initiated by the burn through.

4. PG/Carbitex

Chamber SL-1, fired previously for 40 seconds (Reference 2) was fired for 40 and 105 seconds during Runs 11 and 12, respectively.

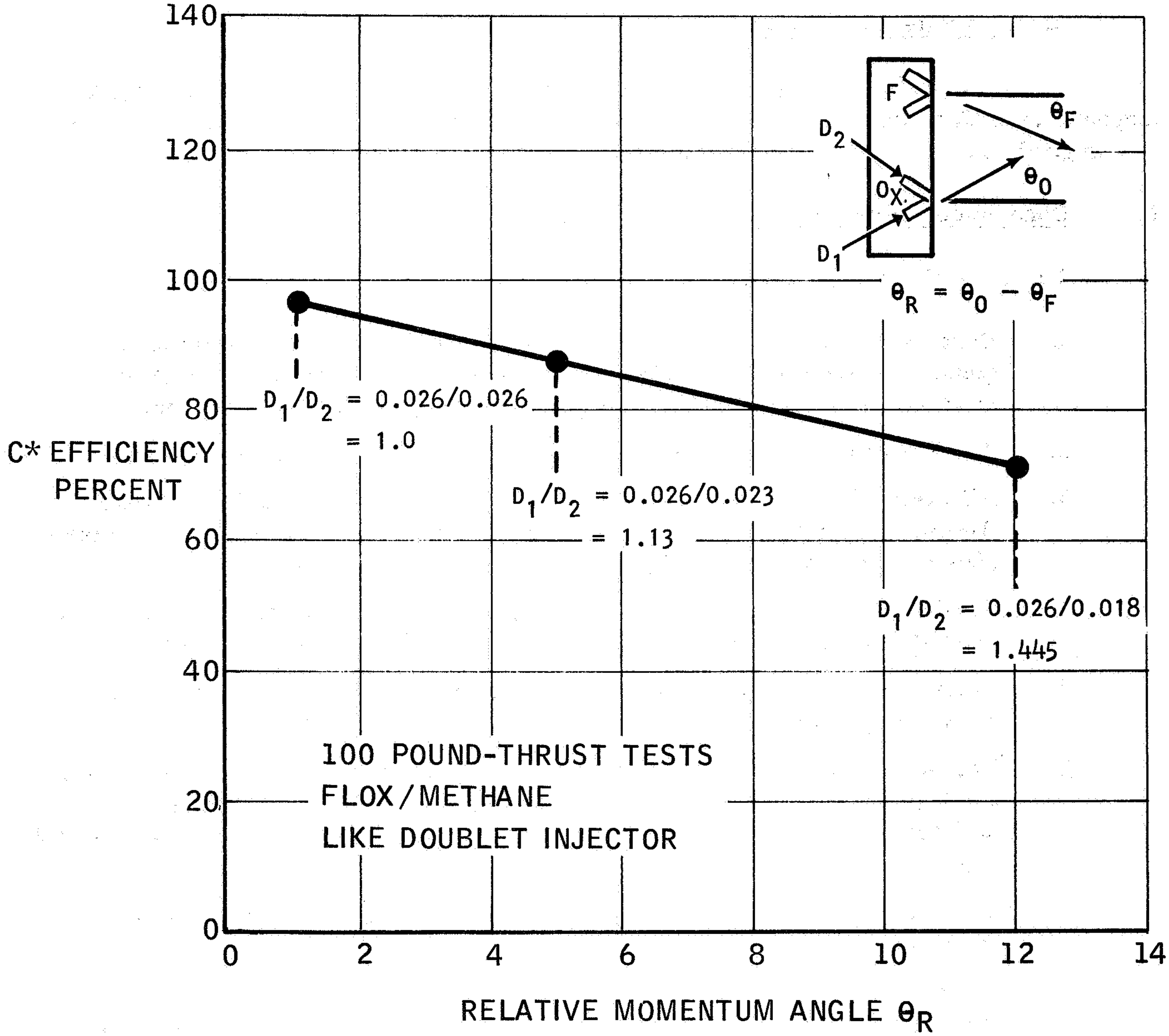


Figure 14. - Effect of Relative Momentum Angle vs. Performance

The chamber pressure varied erratically during Run 12 because of carbon buildup in the throat which periodically was ejected, as shown in Figure 15. The overall erosion rate was 0.15 mils/sec (0.00038 cm/sec). Post test examination of the chamber revealed heavy carbon deposits about two inches (5.08 cm) downstream of the injector face, and thin carbon deposits in several portions of the throat. The rest of the combustion chamber and contraction region was free of carbon deposits. The PG had been smoothly eroded away in a 90^{o} segment of the contraction region, but no evidence of leakage through the Carbitex was found. There were about eight hairline cracks in the throat PG coating, which did not cause any further damage to the Carbitex 713.

5. Carbitex (Uncoated)

An uncoated Carbitex 713 chamber was given four test firings. During the longest run of 61 seconds (Run 19), the throat erosion was 0.41 mils/sec. The chamber was in good condition after the tests except for the throat erosion.

B. Conclusions from 100-Pound-Thrust Firings

The general test conclusions are as follows:

1. Carbon deposition on the chamber walls and nozzle throat in significant quantities occurred in nearly all runs over 30 sec in duration. Higher mixture ratio operation appeared to reduce the amount of deposition.
2. The PG/Carbitex chamber material exhibited the least throat erosion.
3. All runs exhibited soft starts using a gaseous F_2/gaseous CH_4 lead with the engine at ambient temperature. This procedure resulted in some mixed phase operation when the liquid propellants were introduced.
4. The lower performance Runs 16 through 19 showed significantly less carbon deposition. This may have been due to lower chamber wall temperature.
5. Variation in differential momentum angle between the oxidizer and fuel doublets produced significant effects upon C* performance.
6. The maximum single run duration of 105 sec (Run No. 12) was obtained with a PG/Carbitex chamber. A maximum chamber pressure increase of 30% occurred which subsequently reduced to the nominal prior to the end of the run. Minimal throat erosion was exhibited.
7. The maximum accumulated time on one chamber was 185 sec (also the PG/Carbitex chamber).
8. In general, chamber pressure tended to show an increase from nominal for run durations over approximately 30 seconds. An exception is Run 8 during which a steady chamber pressure was maintained for 60 seconds.

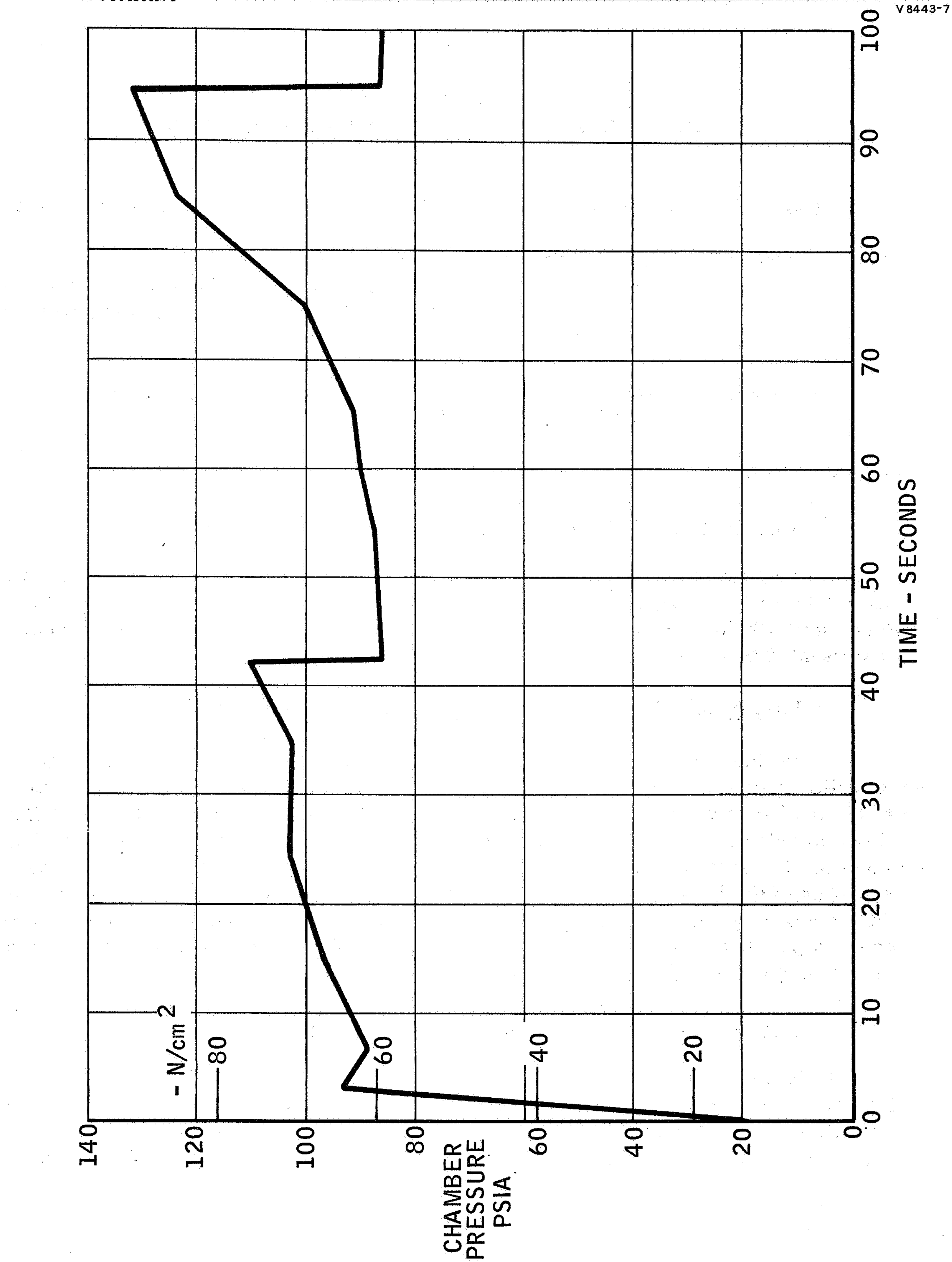


Figure 15. - Chamber Pressure Variation of 100-Pound Thrust Engine for Run 12

SECTION VI
TEST FIRINGS OF 25 POUND-THRUST CHAMBERS

Test firings of 25 pound thrust engines with FLOX/LPG were conducted in two tasks:

TASK IV Uncooled and Streak Chamber Testing
February 18, 1970 through February 25, 1970 (FLOX/methane) and April 6, 1970 through April 24, 1970 (FLOX/methane and FLOX/propane)

TASK VI Graphite and copper chamber testing with FLOX/methane
December 1 through December 3, 1970

The test results are discussed below:

A. Task IV - Uncooled and Streak Chamber Testing - February Tests

Test firings of the 25 pound thrust engine were initiated on February 18, 1970 and a total of ten firing test runs with 82.5% FLOX*/methane were accumulated during February with the configuration shown in Figure 1. A run and data summary tabulation is presented in Table III.

Injector S/N 002 - Axial Flow Film Cooling Ring (Runs 1 and 2)

During Runs 1 and 2 using the expanded swirl injector (S/N 002) and single propellant valves, the firings were programmed for a run duration of 0.5 second by mechanical timer. It became evident that for this time duration insufficient propellant flow was established to accomplish ignition. This fact was revealed through a series of subsequent cold flow tests on both the fuel and oxidizer systems which indicated partial two-phase flow during the start-up transients which caused propellant flow reduction. During this series of cold flows, a small leak occurred through the teflon coated Ominseal on the oxidizer port between the injector and valve. The S/N 002 injector was removed from the test stand and the slightly etched sealing face was resurfaced.

Injector S/N 001 - Axial Flow Film Cooling Ring (Runs 3 to 8)

Run durations were increased on Runs 3 through 8 using the unexpanded swirl injector (S/N 001), the axial film cooling ring (30%), and the bipropellant valve. Smooth ignition occurred during the transient propellant flow buildup. By maximizing the cooling on the injector head, the fuel flows were stabilized at the design condition within

*82.5 Wt% F_2, 17.5 Wt% O_2

TABLE III

TEST FIRING SUMMARY - TASK IV - FEBRUARY 1970 TESTS
25 POUND-THRUST FLOX/METHANE

RUN NO.	DATE	CHAMBER AND INJECTOR	RUN DURATION SEC	CHAMBER PRESSURE PSIA(N/cm^2)	MIXTURE RATIO	C* FT/SEC (m/SEC)	C* EFF. %	PURPOSE	REMARKS
1	2/18/70	CU L* = 17 in. (43.2 cm) Inj. S/N 002	0.5	- -	- -	- -	- -	Ignition, performance (no head cooling)	No propellant flow
2	2/18/70	CU L* = 17 in. (43.2 cm) Inj. S/N 002	0.5	- -	- -	- -	- -	Ignition, performance with head cooling	"
Made series of cold flow runs on both ox. and fuel individually to determine flow rate transient.									Leak in ox.
3	2/19/70	Poco L* = 17 in. (43.2 cm) Inj. S/N 001	8.0	31.9 (22.0)	1.99	3850 (1173)	64	Ignition, performance Minimum head cooling	Good ignition. Transient fuel and ox. flows
4	2/19/70	Poco L* = 17 in. (43.2 cm) Inj. S/N 001	8.0	42.9 29.6	2.41	4450 (1358)	71	Same as Run 3 with increased head cooling	"
5	2/19/70	Poco L* = 17 in. (43.2 cm) Inj. S/N 001	12.0	62.9 (43.3)	3.0	6040 (1840)	94	Same as Run 3 with increased head cooling	Good ignition. Fuel flow near steady state. Ox. flow transient. Hardware O.K.
6	2/23/70	CU L* = 17 in. (43.2 cm) Inj. S/N 001	20.0	74.9 (51.5)	3.25	6000 (1830)	91.2	Ignition, performance Maximum head cooling	Good ignition. Fuel flow steady. Ox. flow transient
7	2/23/70	CU L* = 17 in. (43.2 cm) Inj. S/N 001	30.0	91.9 (63.2)	3.7	6480 (1978)	96.4	Same as Run 6	Same as Run 8
8	2/23/70	CU L* = 17 in. (43.2 cm) Inj. S/N 001	30.0	101.4 (70.0)	4.34	6630 (2020)	96.5	Repeat Run 6 at higher O/F	Good ignition. Both fuel and ox. flows steady. Cooling ring burned.
9	2/25/70	Poco L* = 11 in. (28 cm) Inj. S/N 001	5.0	55.4 (38.1)	3.14	4630 (1410)	71	Performance and inj. durability	Good ignition. Flow not stabilized.
10	2/25/70	Poco L* = 11 in. (28 cm) Inj. S/N 001	5.0	88.3 (60.8)	3.59	6650 (2030)	99	Performance	Good ignition. Higher O/F setting. Flow not stabilized, but ox. transient reduced. Shroud length cut.

approximately 5 seconds. However, the oxidizer system required considerably longer (up to 20 seconds) for stabilized flow to occur. Stabilized propellant flows were achieved during a 30 second firing on Run 8. The C* performance for the unexpanded swirl injector, S/N 001, with the 30% axial flow film injection and 17-inch (43.2 cm) L* chamber was in excess of 95% of theoretical for the mixture ratio values tested with FLOX/methane.

The primary heat leak regions in the propellant systems causing the transient two-phasing operation were isolated to: (1) the short lines (approximately 6 inches) (15.24 cm) connecting the conditioned propellant supply to the engine valve inlet; (2) the engine valve; and (3) the short length (approximately 2 inches) (5.08 cm) of stand-off tubing from the valve seat to the injector manifold.

At the conclusion of Run 8, the engine was disassembled for inspection and it was found that erosion had occurred in a localized section of the film cooling ring cup.

Injector S/N 001 - Shrouded Film Cooling Ring (Runs 9 and 10)

For Runs 9 and 10 the shrouded film cooling ring was installed and the cup depth was reduced from 0.157 inches (0.399 cm) to 0.067 inches (0.17 cm) to reduce heat transfer into the edge of the ring. The reduction in cup depth was accomplished by machining the back face of the film cooling ring to make the ring thinner (Figure 1). Runs 9 and 10 were performed with the S/N 001 injector and the modified thin film cooling ring with the shroud. Propellant flow rates were not stabilized during the 5 second firing of Run 9 at a mixture ratio of 3.14. During Run 10, at a mixture ratio of 3.59, the oxidizer flow rate was close to stabilization. Inspection of the engine after Run 10 showed that the shroud had been burned back as expected to an equilibrium length. The shroud lip had been consumed quite uniformly from an original length of 0.5 inches (1.27 cm) to a length of 0.2 inches (0.508 cm). After Run 10, the shroud was machined to an even length of 0.2 in. (0.508 cm) and the engine was reassembled. Prior to another firing run, an oxidizer cold flow was performed to check the starting transient after inclusion of additional LN_2 cooling on the oxidizer inlet line. At approximately 4 seconds of a timed 5-second cold flow run, the oxidizer seal at the valve-to-injector interface failed and the resulting combustion products caused extensive injector damage.

It was concluded after a study of the failure that a slight leak of FLOX past the Omniseal had started a reaction which then proceeded to burn out the oxidizer manifold.

B. Task IV - Uncooled and Streak Chamber Testing - April Tests

Design changes made at the conclusion of the February tests were as follows:

1. Replaced Omniseal (Teflon and metal coil) with a gold plated metal V-seal.
2. Reduced the ring thickness and beveled the corner of the cup formed by the film cooling ring surrounding the injector core.
3. Relocated the chamber pressure tap to the gap between the chamber flange and the film cooling ring, allowing a full 360 degree coolant manifold in the film cooling ring.
4. Installed a deflection ring inside the film cooling manifold to increase the velocity of the coolant in the manifold and promote self-cooling.

The revised design of the injector assembly is shown in Figure 16.

Test firings were resumed on April 6, 1970 using the configuration shown in Figure 16. A total of fifty test firings were made with an accumulated run time of 1,153 seconds. Both propane and methane were used as liquid fuels. Mixture ratios ranged from 2.14 to 5.44. Film cooling by 27% and 47% of the fuel was used. The nominal chamber pressure was 100 psia (68.9 N/cm^2).

Hardware design modifications made after the initial 25 pound test firings in February were successful in eliminating the previous problems of injector heating and FLOX seal failure.

The C* efficiency ranged from 98% to 84% depending on mixture ratio, percent film cooling and L*.

The major conclusions drawn from the test firing results are as follows:

1. The conditions of wall temperature and local mixture ratio which would allow a graphite chamber to run without either carbon deposition or chemical erosion were not determined during the engine test firing program. A more controlled test technique would be required to determine such conditions.
2. Carbon deposition on the injector film cooling plate and chamber walls is so extensive that attainment of an 1,800 second firing does not seem feasible with liquid fuel film cooling of graphite chambers.
3. Carbon deposition is less using methane than when using propane.
4. Thermal conditioning control of propellants is critical. The data indicates two phase flow to some degree for nearly all runs during the initial periods of the run. Two phasing is most pronounced with methane and results in C* performance degradation.

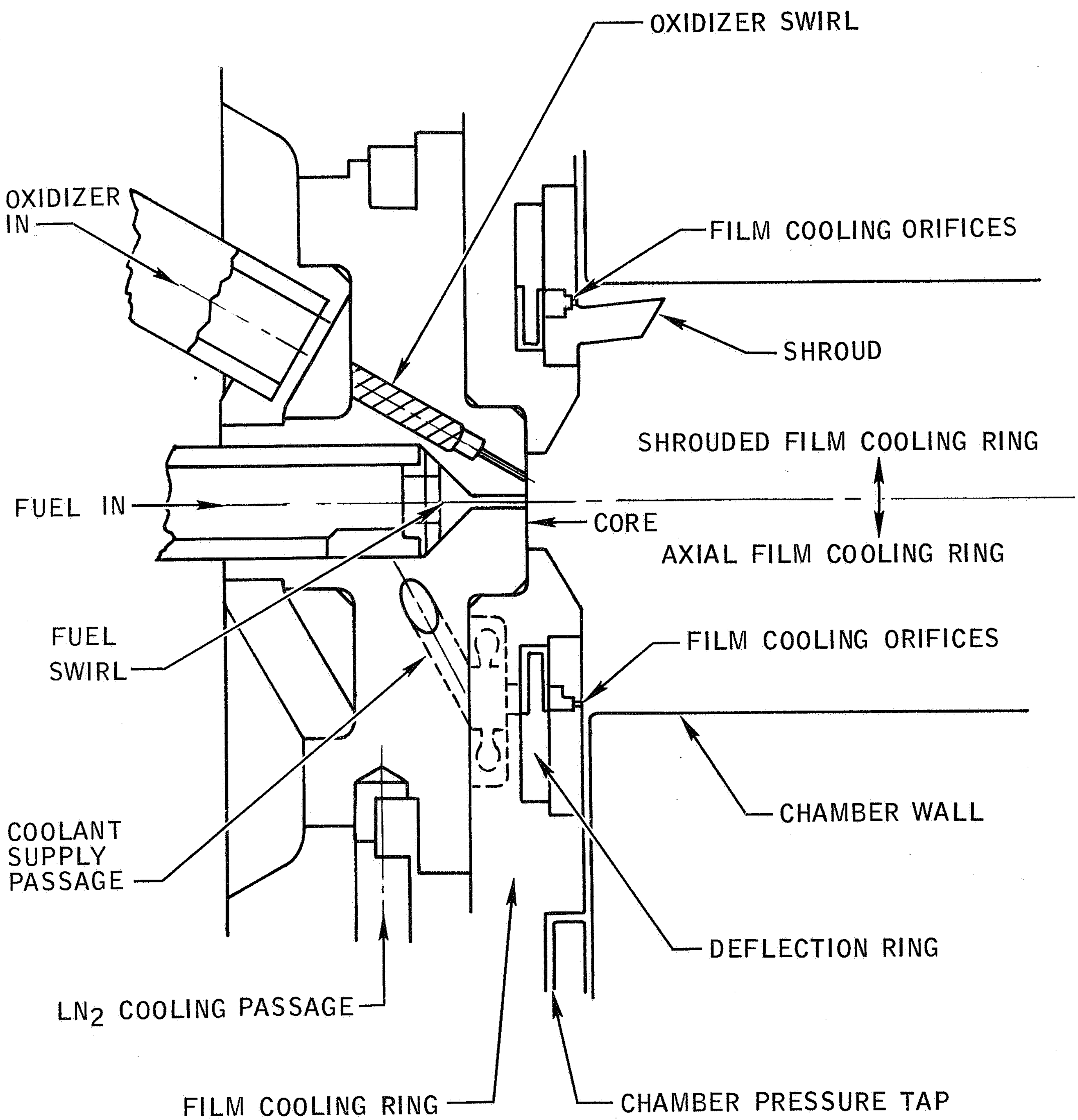


Figure 16. - Revised Injector Core and Film Cooling Ring Assembly
Task IV - April 1970

Hardware Description

Injector S/N 002

The expanded swirl injector S/N 002 was unchanged from its original configuration except for a minor modification to reduce the depth of the central cup within the film cooling ring.

Shroud Film Cooling Ring

A shrouded film cooling ring (Figure 17) was fabricated after the February tests which had a reduced length shroud of about 0.20 inch (0.508 cm). The plate had 24 equally spaced 0.003 inch (0.00762 cm) film cooling holes with axial alignment. The shroud lip was cold worked to an O.D. which exceeded the base diameter (0.650 in.) (1.65 cm) of the film cooling holes. Therefore, all film cooling jets impinged on the outer lip of the shroud. The end of the shroud was cut to a sharp edge to eliminate curl-under of the jets which was observed during water flow. The film cooling from this ring was 47% of the total fuel flow, based on water flow calibration. The shroud was made of Nickel 200.

Axial Film Cooling Ring

A film cooling ring with 12 axial film cooling holes (0.003 in.) (0.00762 cm) was used to inject coolant parallel to the chamber wall. The basic diameter of the whole circle was 0.660 inch (1.68 cm). The holes in both rings were made by FLOX. The axial film cooling ring was found by water flow tests to use 27% of the total fuel flow for film cooling.

Film Cooling Ring Assembly

The complete film cooling plate assemblies were made in the same manner for both the shroud film cooling ring (47%) and the axial film cooling ring (27%). The assembly (Figure 16) was different from the assembly (Figure 1) used in February in several important features.

1. Pressure Tap

The pressure tap was relocated to a point on a 1.5 inch (3.81 cm) diameter, open to the chamber pressure within the gap between the chamber flange and the film cooling ring. Therefore, the film cooling manifold could extend around the complete circumference, unlike the original design, in which a 20 degree arc of the manifold was closed to allow installation of the pressure tap. This region was, therefore, uncooled in the in the previous test program, which probably contributed to the overheating of the 27% film cooling ring when using methane.

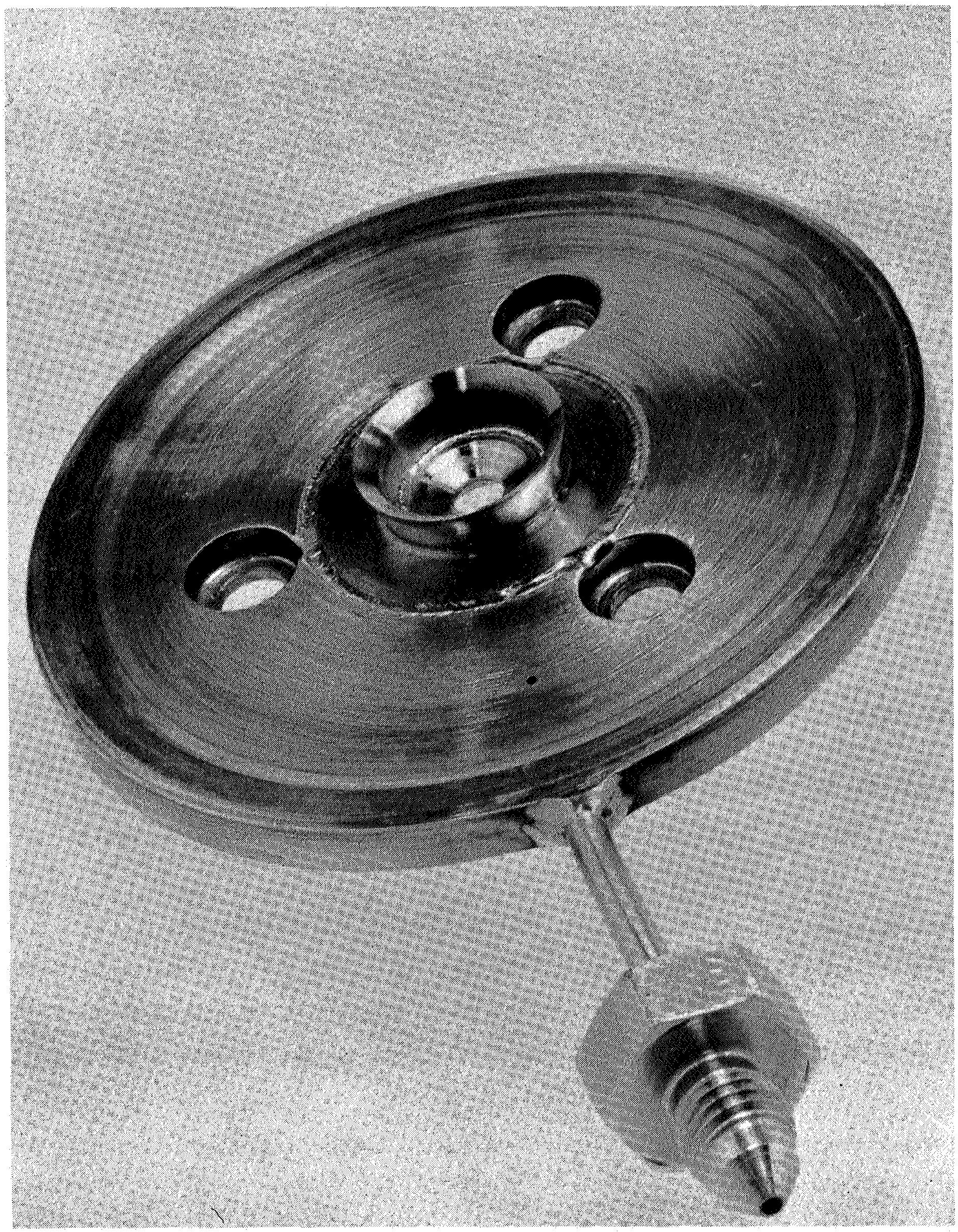


Figure 17. - Shroud Film Cooling Ring for Task IV Tests - April 1970

2. Ring Thickness

The overall thickness of the film cooling ring assembly was 0.180 inch (0.457 cm) and the cup lip was chamfered 120 degrees to give a cup depth of 0.032 inch (0.081 cm) compared to the 0.067 inch (0.17 cm) depth used in the final April test firings. This design successfully eliminated any overheating or chemical erosion of the cup.

3. Deflector Ring

A deflector ring was placed inside the cooling manifold. This created a high velocity of coolant flow within the manifold, moving radially toward the film cooling holes. This design change was also intended to increase the cooling of the film cooling ring.

4. Injector S/N 003

Injector S/N 003 (unexpanded swirl) was made by rework of S/N 001 injector which had been partially damaged during burn out of the teflon coated Omniseal during FLOX cold flow in February. New swirl elements made of Nickel 200 were made for the injector. The S/N 003 injector was not used during the test program because the S/N 002 injector was completely satisfactory. The unexpanded swirl injector would have been used if the graphite chambers had shown that chemical erosion was the major problem. However, carbon deposition on the chamber and injector was the major problem, and it was thought that an expansion of FLOX spray would be best for combating the carbon deposition.

Run Summary

A summary of the hardware changes, test objectives of each run, and engine performance is given in Table IV.

1. 76% FLOX/Propane

Runs 11 through 35 were made with 76% FLOX and propane. Engine performance ranged from about 90% to 98% C* efficiency, as shown in Figure 18. The results of each series of runs are discussed below.

Runs 11 to 15

Runs 11 to 15 were made with the copper heat sink chamber with L* of 11 inches (28 cm), the S/N 002 injector (expanded swirl), and the 47% shroud film cooling ring (Figure 17). These runs were to get performance data at mixture ratios from 2.14 to 3.24. The C* efficiency during these runs was from 94% to 97.5%, except for Run 12, which produced 90.5% C*. The shroud was in good condition after Run 15 except for a melted lip at one point.

TABLE IV

TEST FIRING SUMMARY - TASK IV - APRIL 1970 TESTS
25 POUND-THRUST FLOX/METHANE AND FLOX/PROPANE

RUN NO.	DATE	CHAMBER AND INJECTOR	RUN DURATION SEC	MIXTURE RATIO O/F	C* FT/SEC (m/SEC)	C^* Eff. %	CHAMBER PRESSURE PSIA (N/cm^2)	PURPOSE	REMARKS
11	4/6/70	CU L* = 11 in. (28 cm) Inj. S/N 002 47% shroud film cooling biprop. valve	10.0	2.14	6072 (1850)	96.2	105.8 (72.8)	76% FLOX/Propane per formance. Cold oxidizer	Good ignition. Fuel and oxidizer flows stabilized.
12	4/6/70	"	10.0	2.45	5795 (1762)	90.5	100.2 (69.0)	"	Good ignition. Fuel and oxidizer flows stabilized.
13	4/6/70	"	15.0	2.39	6001 (1830)	94.0	104.3 (72.0)	"	"
14	4/6/70	CU L* = 11 in. (28 cm) Inj. S/N 002 47% shroud film cooling biprop. valve	10.0	3.24	6472 (1975)	97.5	110.3 (76.0)	76% FLOX/Propane per-formance. O/F 2.0 to 3.0 cold oxidizer purge.	Good ignition flows
15	4/6/70	"	10.0	Chamber pressure tap plugged				"	"
16	4/7/70	POCO streak Inj. S/N 002 47% shroud film cooling biprop. valve	10.0	Data no good				76% FLOX/Propane streak characteristics and de-position. Shroud. Low O/F. Check run	Good ignition. Run OK P_c steady.
17	4/7/70	"	24.0	2.74	6076 (1852)	93.5	96.2 (66.3)	"	Good ignition. P_c increased.
18	4/8/70	CU L* = 11 in. (28 cm) Inj. S/N 002 27% axial film cooling biprop. valve	10.0	2.32	6422 (1960)	99.	111.9 (77.0)	76% FLOX/Propane per-formance at lower F.C. flow. O/F survey.	Good ignition. All parameters at desired values. P_c steady.
19	4/8/70	"	15.0	2.44	6305 (1920)	98.6	108.3 (74.6)	"	"
20	4/8/70	"	15.0	2.44	6200 (1890)	96.9	106.5 (73.4)	"	"
21	4/8/70	"	15.0	2.47	6067 (1850)	94.6	103.8 (71.5)	"	"
22	4/8/70	"	15.0	2.92	6380 (1946)	97.6	110.6 (76.1)	"	"

TABLE IV (Continued)

TEST FIRING SUMMARY - TASK IV - APRIL 1970 TESTS
25 POUND-THRUST FLOX/METHANE AND FLOX/PROPANE

RUN NO.	DATE	CHAMBER AND INJECTOR	RUN DURATION SEC	MIXTURE RATIO O/F	C* FT/SEC (m/SEC)	C^* Eff. %	CHAMBER PRESSURE PSIA(N/cm^2)	PURPOSE	REMARKS
23	4/8/70	Same as 22	15	2.96	6405 (1950)	97.8	110.6 (76.1)	Repeat 22	Same as 22
24	4/9/70	POCO streak $L^* = 17$ in. (43.2 cm) Inj. S/N 002 27% axial film cooling biprop. valve	20.0	2.26			129.3 (89.0)	76% FLOX/Propane streak and deposition. Low O/F	Good ignition. P_c increased.
25	4/9/70	POCO/streak $L^* = 11$ in. (28 cm) Inj. S/N 002 27% axial f.c. biprop. valve	10.0	4.48	6900 (2105)	101	112.8 (77.6)	76% FLOX/Propane streak/ deposition. High O/F	Good ignition. All parameters at desired values. P_c steady.
26	4/9/70	Same	25.0	4.48	7405 (2260)	-	119.4 (82.4)	Same	P_c increased.
27	4/10/70	Copper Cham. $L^* = 11$ in. (28 cm) Inj. S/N 002 27% f.c. biprop. valve	10.0	2.98	6512 (1985)	95.9	121.2 (83.5)	76% FLOX/Propane performance at high O/F	Good ignition. All parameters at desired values. P_c steady.
28	4/10/70	"	10.0	3.74	6286 (1915)	93.	96.1 (66.3)	"	"
29	4/10/70	"	10.0	4.24	6164 (1880)	90.3	101.4 (69.8)	"	"
30	4/10/70	"	10.0	4.24	6261 (1910)	91.7	103. (71.0)	"	"
31	4/10/70	"	10.0	4.65	6367 (1940)	93.2	103. (71.0)	"	"
32	4/10/70	"	10.0	4.60	6407 (1955)	93.8	103.8 (71.5)	"	"
33	4/10/70	"	25.0	3.74	6276 (1910)	92.8	94.1 (64.9)	"	"
34	4/13/70	POCO/PG Sleeve $L^* = 17$ in. (43.2) Inj. S/N 002 27% axial f.c. biprop. valve	20.0	5.09	6224 (1900)	91.7	98.5 (67.9)	Streak and carbon deposition data	P_c increased
35	4/14/70	Same except 46% shroud f.c.	20.0	4.64			92.1 (63.5)	Streak and carbon deposition data	P_c increased

TABLE IV (Continued)

TEST FIRING SUMMARY - TASK IV - APRIL 1970 TESTS
25 POUND-THRUST FLOX/METHANE AND FLOX/PROPANE

RUN NO.	DATE	CHAMBER AND INJECTOR	RUN DURATION SEC	MIXTURE RATIO O/F	C* FT/SEC (m/SEC)	C^* Eff. %	CHAMBER PRESSURE PSIA(N/cm^2)	PURPOSE	REMARKS
36	4/16/70	Inj. S/N 002 47% f.c. Copper Cham. L^* = 7 in.(17.8 cm)	10.0	4.38	5315 (1620)	76.6	81.8 (56.4)	76% FLOX/Methane Performance over O/F range 4.0 to 5.3	Change to 76% FLOX/Methane Good ignition. All parameters at desired values. P_c steady
37	4/16/70	"	15.0	4.1	5150 (1570)	74.	80.8 (55.6)	"	Good ignition. All parameters at desired values. P_c steady
38	4/16/70	"	15.0	4.04	5140 (1565)	74.2	80.4 (55.4)		Good ignition. All parameters at desired values. P_c steady
39	4/16/70	"	15.0	4.62	5200 (1585)	74.6	80.5 (55.5)	"	"
40	4/16/70	"	15.0	4.62	5560 (1697)	80.0	86.3 (59.5)	"	"
41	4/16/70	"	15.0	4.62	5640 (1720)	81.2	87.1 (60.0)	"	"
42	4/16/70	"	15.0	5.16	5810 (1770)	84.2	90.3 (62.2)	"	"
43	4/16/70	"	25.0	5.16	6100 (1860)	88.4	94.1 (64.9)	"	Injector manifold pressure P_{om}, P_{fm} stabilized.
44	4/16/70	"	30.0	4.13	6070 (1850)	87.5	93.3 (64.3)	"	"
45	4/17/70	Inj. S/N 002 27% f.c. (new plate) POCO/PG Sleeve L^* = 17 in. (43.2 cm)	20.0	5.11	6210 (1890)	89.5	80.8 (55.7)	76% FLOX/Methane Streak and erosion	"
46	4/17/70	Inj. S/N 002 27% f.c. POCO Cham. No sleeve L^* = 11 in. (28 cm)	130.0	5.2	-	-	-	Chamber/injector endurance FLOX/Methane	Several P_c variations Run cut due to large P_c drop. (Chamber attach bolt washers melted).
47	4/22/70	Inj. S/N 002 27% f.c. Copper Cham. L^* = 7 in. (17.8 cm)	30.0	4.3	5640 (1720)	81.	87.8 (60.5)	76% FLOX/Methane Low L^*, Low f.c. Performance, O/F traverse	Good ignition. All parameters steady

TASK IV (Continued)

TEST FIRING SUMMARY - TASK IV - APRIL 1970 TESTS
25 POUND-THRUST FLOX/METHANE AND FLOX/PROPANE

RUN NO.	DATE	CHAMBER AND INJECTOR	RUN DURATION SEC	MIXTURE RATIO O/F	C* FT/SEC (m/SEC)	C^* Eff. %	CHAMBER PRESSURE PSIA(N/cm^2)	PURPOSE	REMARKS
48	4/22/70	Inj. S/N 002 27% f.c. Copper Cham. L^* = 7 in.(17.8 cm)	30.0	4.3	5247 (1600)	75.	81.8 (56.4)	76% FLOX/Methane Low L^*, Low f.c. Performance, O/F traverse	Good ignition. All parameters steady
49	4/22/70	"	30.0	4.91	5584 (1700)	80.5	87.4 (60.2)	"	"
50	4/22/70	"	30.0	5.04	5640 (1720)	81.5	87.8 (60.5)	"	"
51	4/22/70	"	30.0	5.29	5442 (1660)	78.5	85.8 (59.0)	"	"
52	4/22/70	"	30.0	5.44	5127 (1562)	74.5	80.5 (55.5)	"	"
53	4/24/70	Inj. S/N 002 47% f.c. Copper Cham. L^* = 11 in.(28 cm)	15.	4.2	5835 (1778)	84.	89.8 (61.9)	82.5 FLOX/Methane L^* performance High f.c. O/F traverse	Change to 82.5 FLOX Good ignition. P_{om}, P_{f_m} not stabilized
54	4/24/70	"	15.	4.2	5835 (1778)	84.	89.8 (61.9)	"	"
55	4/24/70	"	30.	4.19	5788 (1765)	83.4	81.5 (56.1)	82.5% FLOX/Methane Low f.c. Performance, O/F traverse	Good ignition. All parameters stabilized
56		"	30.	4.84	6114 (1862)	88.1	93.3 (64.2)	"	"
57		"	30.	4.84	6160 (1880)	89.1	94. (64.7)	"	"
58		"	30.	5.16	6216 (1898)	90.	96.5 (66.5)	"	"
59		"	30.	5.16	6261 (1910)	90.5	96.5 (66.5)	"	"
60	4/24/70	Inj. S/N 002 47% axial f.c. POCO L^*= 11 in.(28 cm) PG Sleeve	120	5.16	-	-	88.8 (61.1)	82.5% FLOX/Methane streak Carbon deposition	P_c variation. Chamber failed. Crack in POCO flange bolt hole.

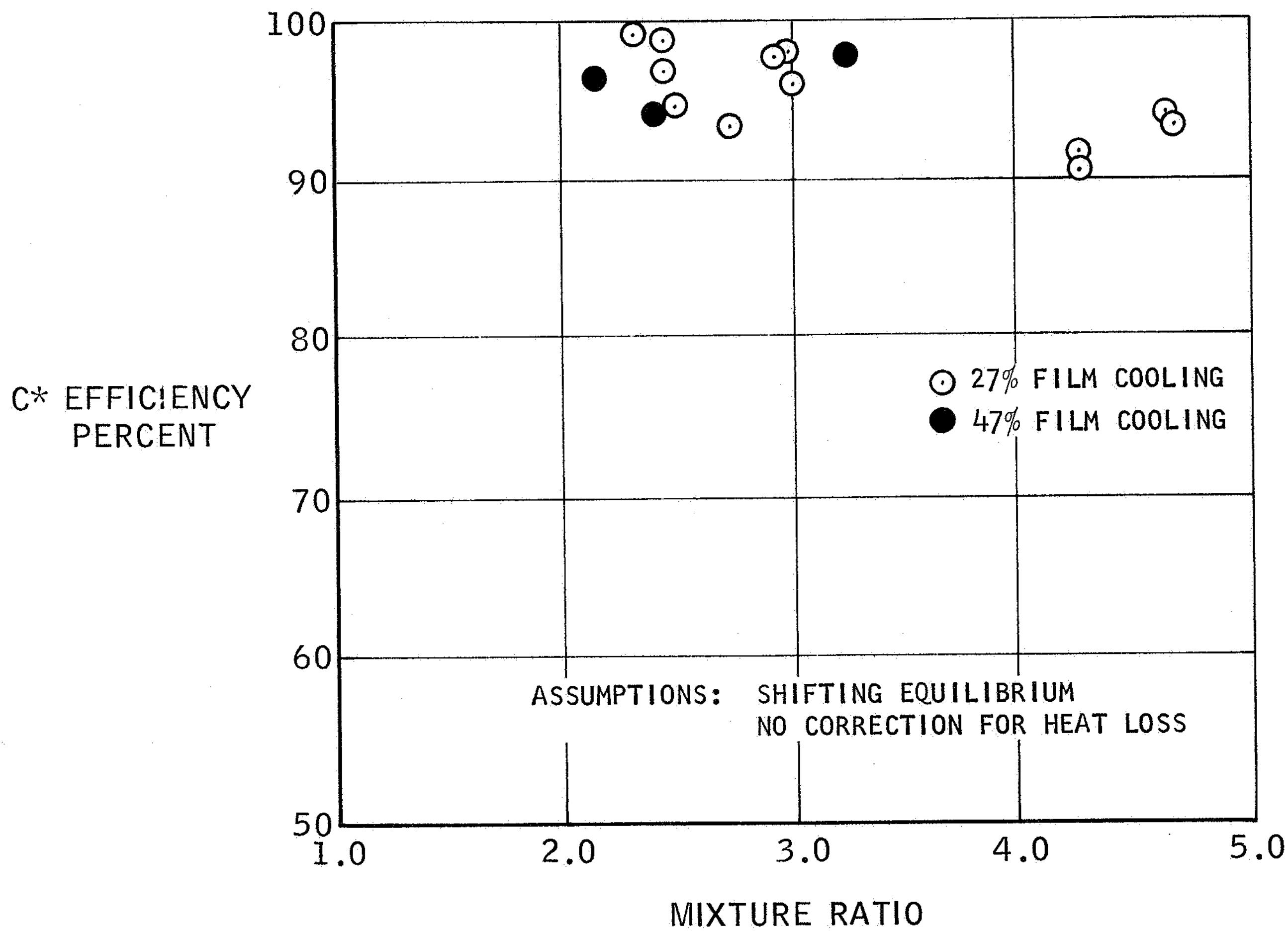


Figure 18. - C* Efficiency - 76% FLOX/Propane Tests - Task IV

The appearance of the injector and film cooling ring after Run 15 is shown in Figure 19. The shroud is difficult to see in this photo because of the carbon deposition on the film cooling ring.

Water flow of the film cooling ring after Run 15 showed that a pin hole leak of fuel had occurred through the EB weld inside of the shroud. The leak impinged on the shroud near the burned spot, indicating that a mixture of leaking fuel and FLOX from the core had caused the burn. The leak was repaired and no further damage was experienced during subsequent runs.

Runs 16 and 17

A POCO streak chamber with an L* of 11 inches (28 cm) and a Pyrolarex streak sleeve was tested for 10 seconds on Run 16 and 24 seconds on Run 17. The mixture ratio during Run 17 was 2.74 and the C* efficiency was 93.5%. The pyrolarex sleeve with carbon deposit is shown after Run 17 in Figure 20.

Runs 18 to 23

Performance of the S/N 002 injector with the 27% film cooling ring was determined with the copper heat sink chamber (L* = 11 inches) (28 cm) during Runs 18 through 23. The C* efficiency was between 94.5% and 99% during these runs, which covered mixture ratios from 2.32 to 2.96.

Run 24

A POCO streak chamber with a Pyrolarex sleeve was tested for 20 seconds with 27% film cooling and a mixture ratio of 2.26 during Run 24. The chamber L* was 17 inches (43.2 cm). The carbon buildup on the chamber and Pyrolarex liner near the injector face is shown in Figure 21. The carbon build-up was as much as 0.050 inch in thickness. Several erosion streaks about 0.010 inch deep were also found in the Pyrolarex sleeve near the injector. The P_c location shown in the photo was used as an index of chamber orientation on the injector.

The exit end and carbon deposition in the throat of the POCO chamber after Run 24 is shown in Figure 22. The chamber pressure had risen to 162 psia (112 N/cm^2) at the end of 20 seconds, which was the reason for terminating the run at that time.

Runs 25 and 26

A POCO streak chamber with a Pyrolarex streak sleeve and an L* of 11 inches (28 cm) was tested at a higher mixture ratio of 4.48 to see if the higher mixture ratio would alleviate the carbon deposition on chamber and throat observed at a mixture

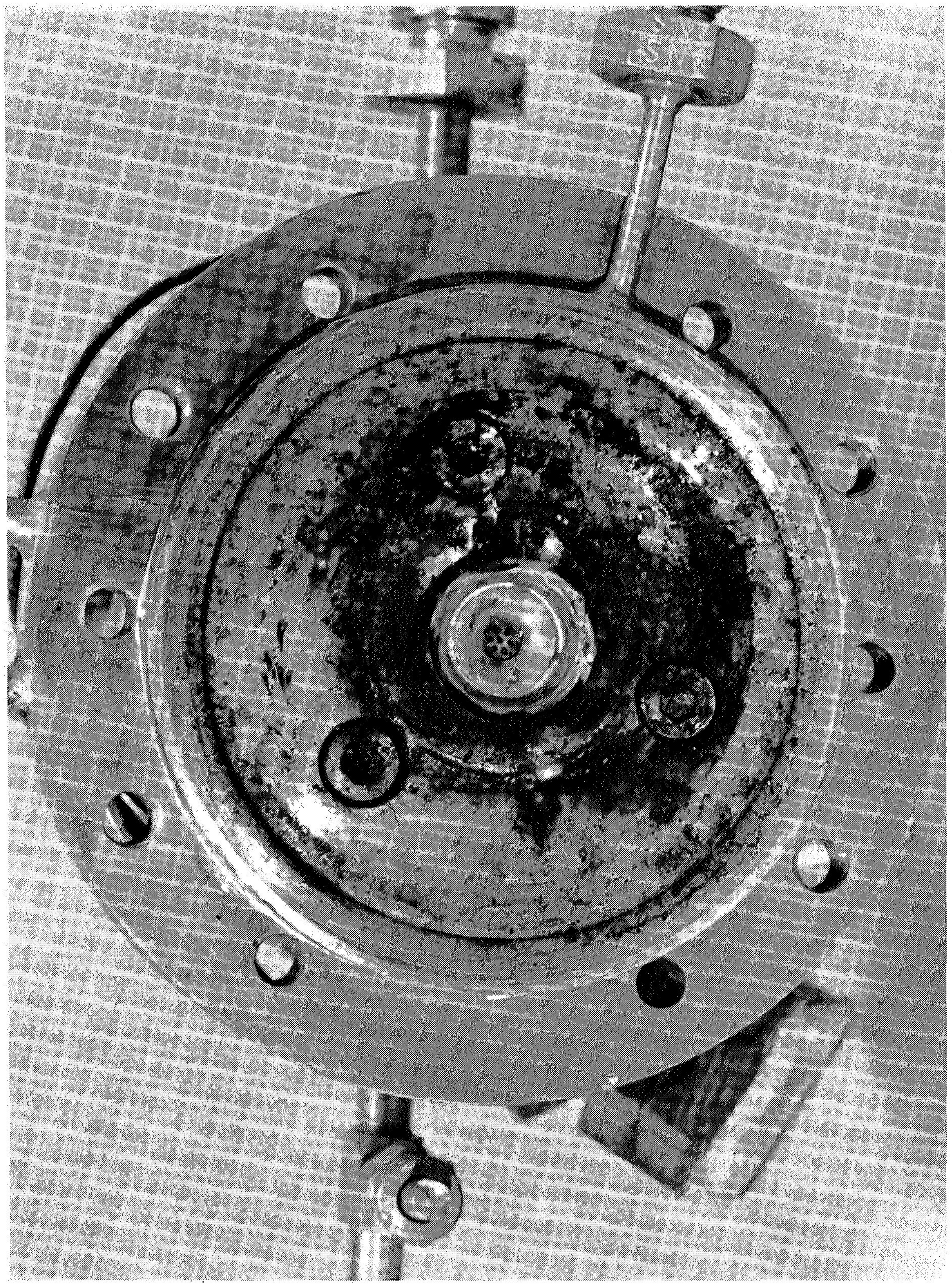


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Figure 19. - Injector S/N 002 After Run 15

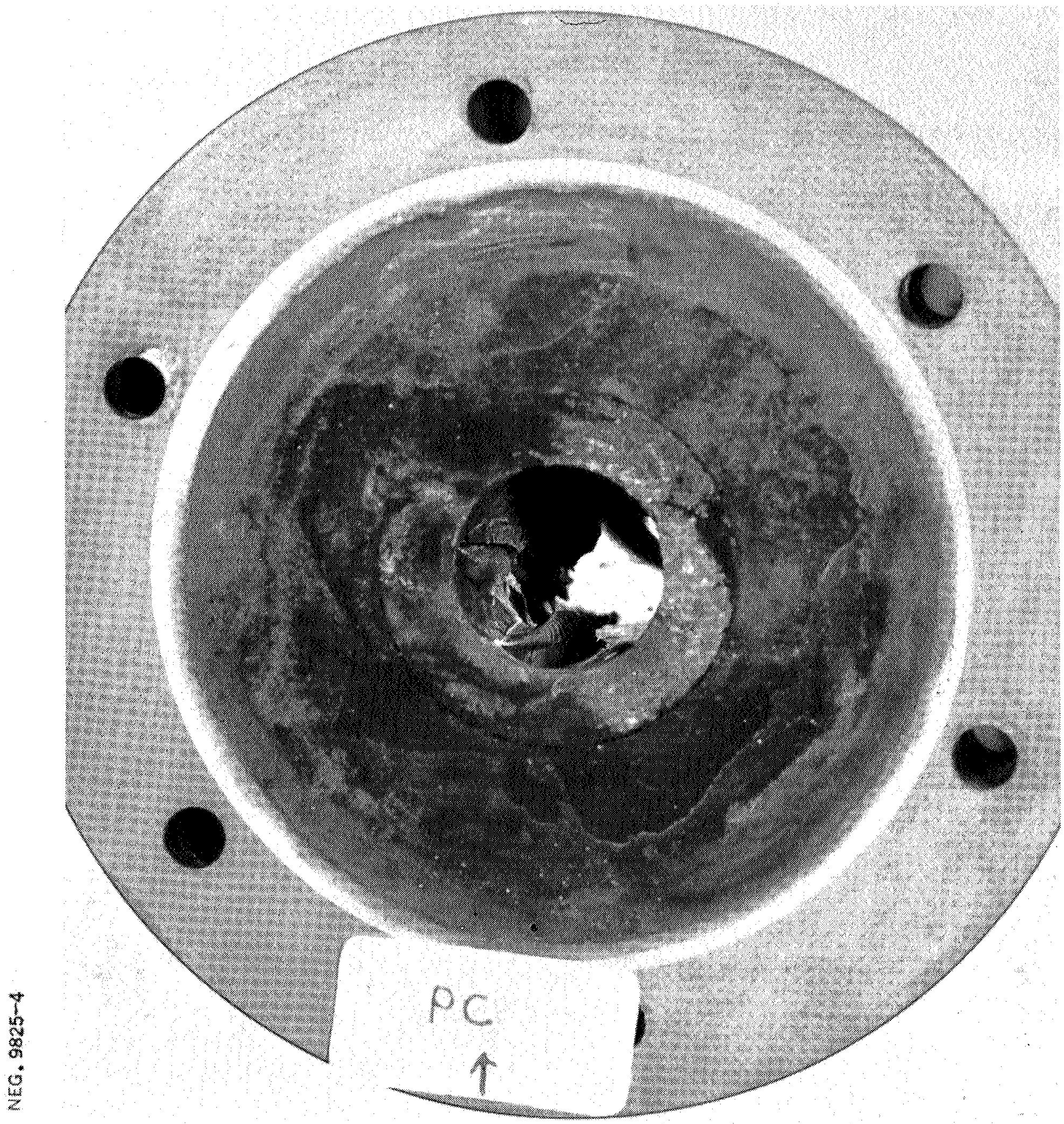

Figure 20. - POCO Streak Chamber with Pyrolarex Sleeve After Run 17

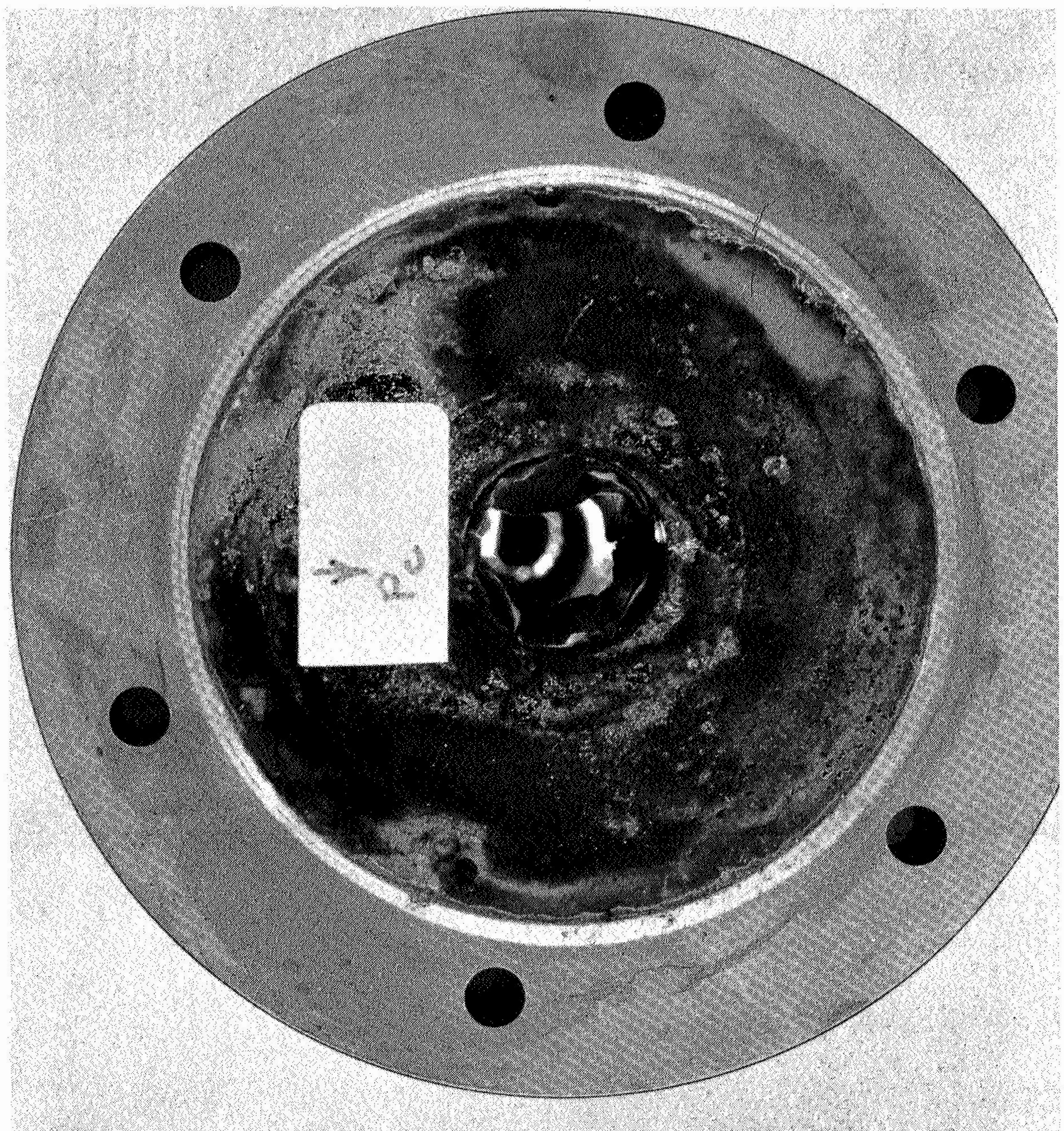

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Figure 21. - POCO Chamber with Pyrolarex Sleeve After Run 24

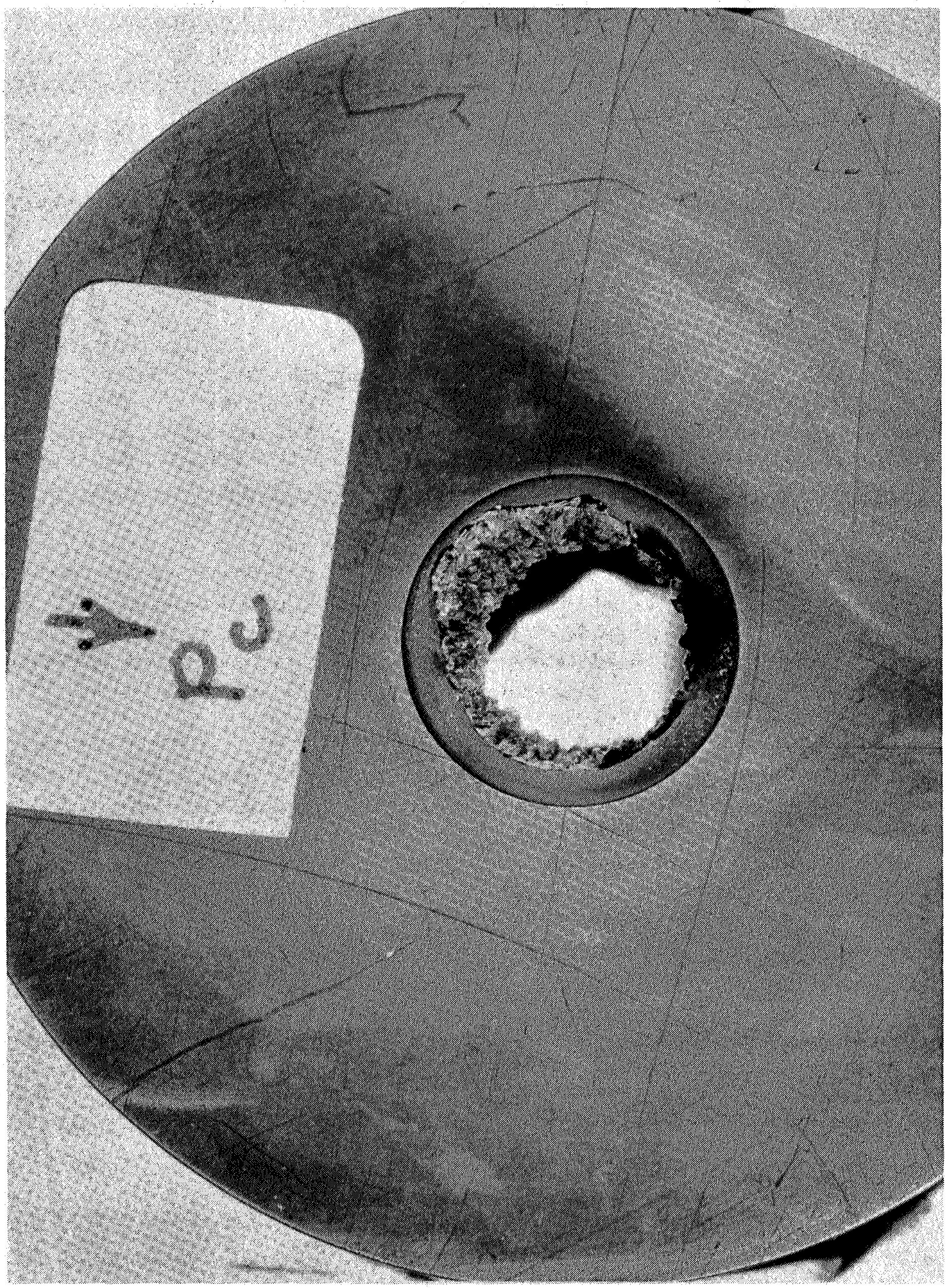

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Figure 22. - POCO Throat After Run 24

ratio of 2.26 during Run 24. No significant change in carbon deposition at the higher mixture ratio could be observed, as shown by the appearance of the throat (Figure 23) and streak sleeve (Figure 24) after Run 25 (10 seconds) and Run 26 (25 seconds) had been completed. The chamber pressure had risen to 162 psia (112 N/cm^2) at the end of Run 26 because of the throat deposition.

Runs 27 to 33

During Runs 27 to 33, engine performance at higher mixture ratios (3.74 to 4.65) was obtained with the copper heat sink chamber, 11 inches (28 cm) L*, and 27% axial film cooling ring. The C* efficiency ranged from 90.3% to 95.9%.

Run 34

Run 34 was a test of a POCO streak chamber at a high mixture ratio (5.09) with 27% film cooling. A pyrolytic graphite sleeve was used instead of a Pyrolarex sleeve. The I.D. of the sleeve was 0.880 inch (2.23 cm) compared to 0.717 inch (1.82 cm) for the Pyrolarex sleeve. The wall thickness of the PG sleeve was about 0.040 inch (0.102 cm) and the length was 2 inches (5.08 cm).

The PG sleeve was removed from the chamber after the 20 second run and was found to have both carbon deposition and erosion through the wall in different locations. Prerun water flow of the cleaned and flushed 27% film cooling ring had shown that some film cooling orifices were plugged. Using the P_c tap as a 1 o'clock reference, the plugged orifices were at 7, 9 and 11 o'clock. Post-run water flow of the ring without cleaning showed that orifices were plugged at 3, 5, 8, 9, 10, 11 and 12 o'clock. The other 5 orifices were still flowing water.

The erosion spot on the PG sleeve was at 9:30, about 0.75 inch (1.9 cm) from the injector face, in the middle of a zone of plugged film cooling holes. However, there was a ridge of carbon buildup at the injector end of the sleeve, about 0.10 inch (0.254 cm) thick, which extended around most of the circumference. The mechanism for providing this carbon is not clear, although it might be caused by recirculation of fuel vapor in the 0.025 inch (0.063 cm) gap between the chamber flange and the film cooling ring. Soot was found on the injector face in this region out to the sealing area after all runs. Repeated efforts to open the film cooling orifices were unsuccessful after Run 34. It was found that by using a 3 mil (0.0076 cm) wire, the orifices were open but carbon or soot was inside the manifold which would cause further plugging. The face plate was machined off and carbon particles were found in the manifold, particularly in the narrow 4 mil (0.0102 cm) gap at the I.D. of the deflector plate. It was concluded that coking had occurred inside the manifold, although the mechanism for this is not clear. A new 12 hole ring was installed after cleaning the inside of the manifold, and this reworked 27% film cooling ring was used in subsequent runs.

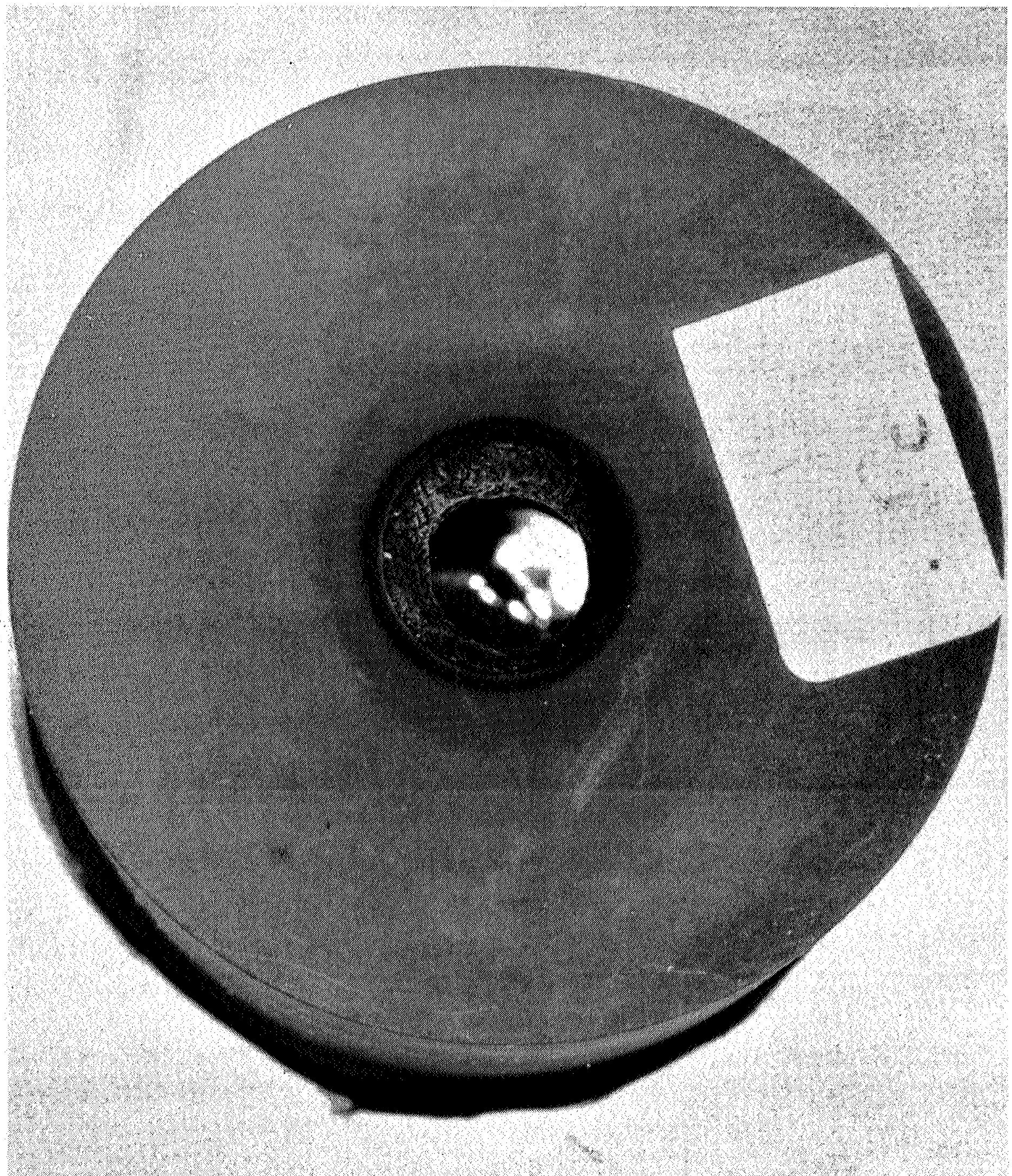
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Figure 23. - POCO Throat After Run 26

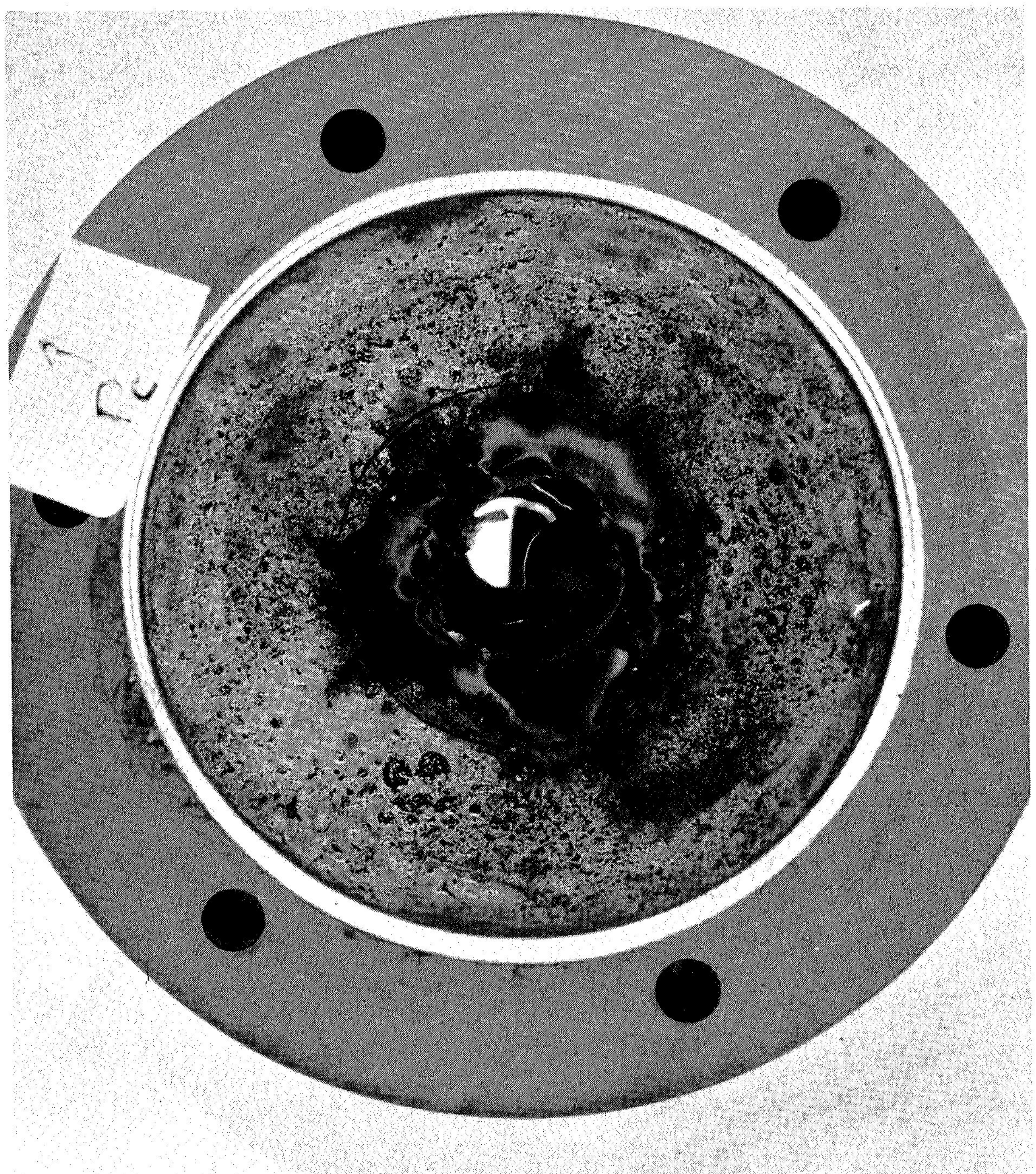

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Figure 24. - POCO Chamber with Pyrolarex Sleeve After Run 26

Run 35

Run 35 was a repeat of Run 34, using a new PG sleeve, except that 47% film cooling was used. There was negligible erosion but more carbon deposit in some regions (Figure 25) than when using 27% film cooling (axial) on Run 34.

The shroud tip was found to be partially burned away over about a 120 degree arc after Run 35. Pre-run water flow of the cleaned and flushed 47% film cooling ring had shown that all orifices were open except 1 at 9 o'clock. Post-run water flow showed that 6 out of 24 orifices were closed or dripping. It was decided that the partially burned shroud would introduce non-axisymmetric cooling of the chamber and so it was machined off before further testing. This resulted in 47% axial flow film cooling.

2. 76% FLOX/Methane

After Run 35, the fuel was changed to methane. The 76% FLOX was used for some runs with methane in order to economically use the test cell occupancy time. C* efficiencies with FLOX/methane ranged from 84% to 90%, as shown in Figure 26, after disregarding the low performance on Runs 47 to 52 caused by a leak in the film cooling manifold.

Run 36 to 44

A short 7 inch (17.8 cm) L* copper chamber was used to determine performance over mixture ratios from 4.04 to 5.16. The 47% film cooling ring (axial flow, shroud removed) was used. Engine performance was low during Runs 26 to 42, which were of 15 second duration. C* efficiency ranged from 74% to 84%. During these 15 second runs, the oxidizer and fuel manifold pressures were not stabilized. Runs 43 and 44 were 25 and 30 seconds in duration, and manifold pressures were stabilized by the end of the runs. The engine performance was about 88% C* on both runs. Carbon deposition on the film cooling ring after Run 44 is shown in Figure 27.

Run 45

Run 45 was made to compare carbon deposition and chamber erosion using methane with deposition and erosion using propane under directly comparable conditions (Run 34). The mixture ratio was 5.11 and the new 27% film cooling ring was used with a POCO chamber containing a PG sleeve in the two inches (5.08 cm) adjacent to the injector face.

After the 20 second run, it was found that there was no erosion evident on the PG sleeve. There was some carbon buildup near the injector face, but much less than had occurred during Run 34 with propane. It was concluded from this test that carbon deposition on the chamber wall near the injector face is much less from methane than from propane. There was no carbon deposition in the chamber or throat during this 20 second run.

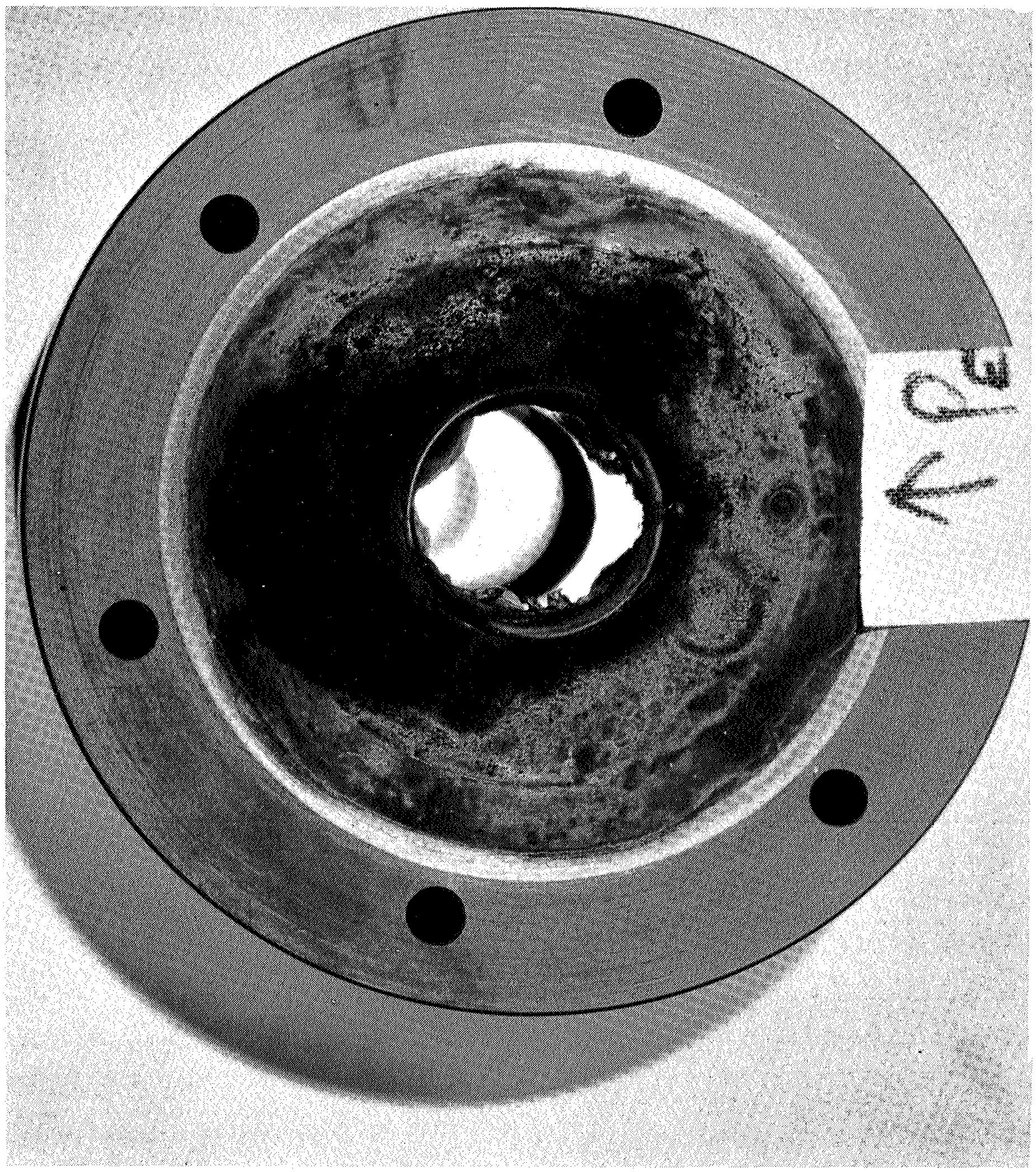

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Figure 25. - POCO Chamber with Pyrolytic Graphite Sleeve After Run 35

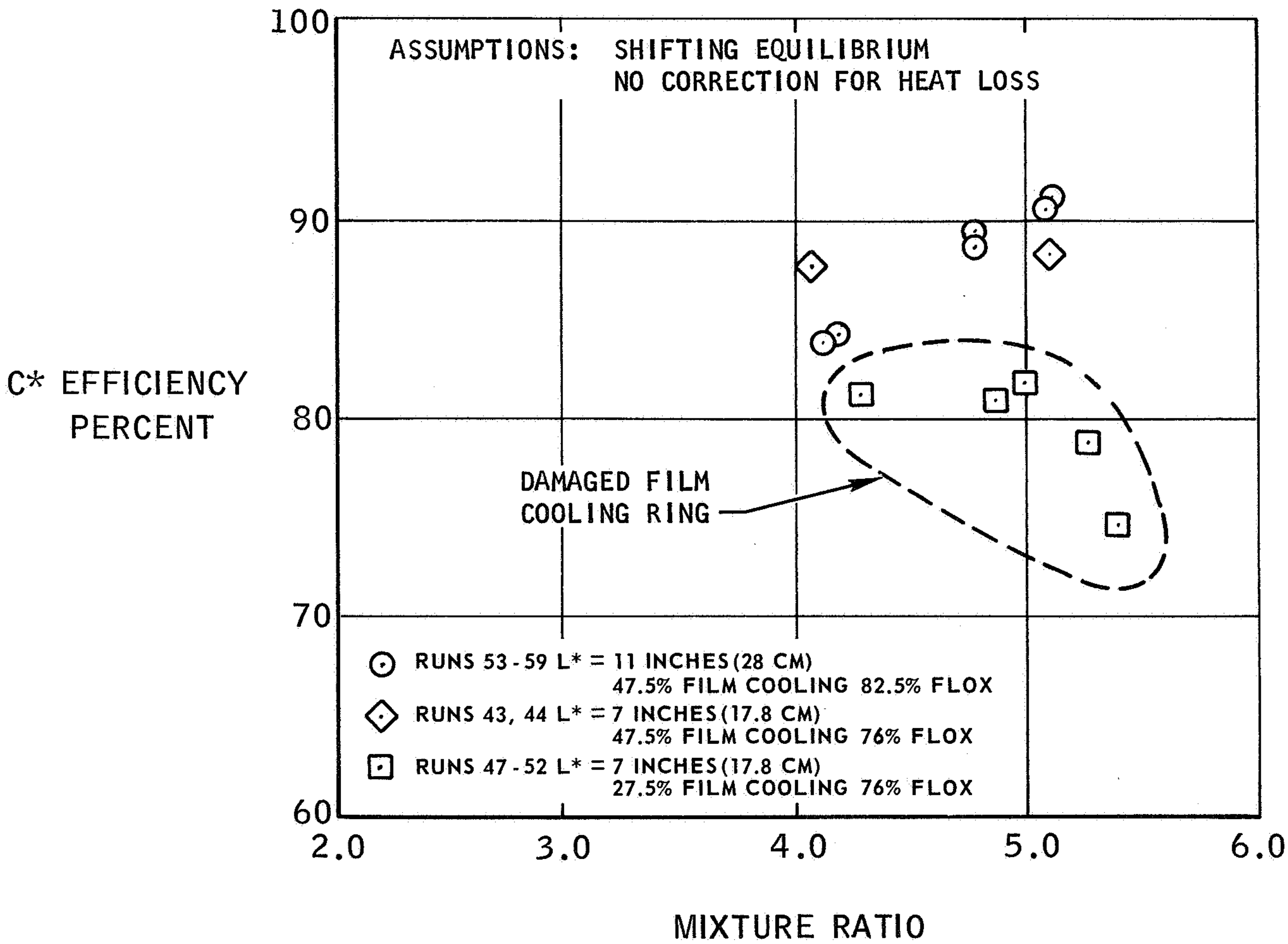

Figure 26. - C* Efficiency - FLOX/Methane Tests - Task IV

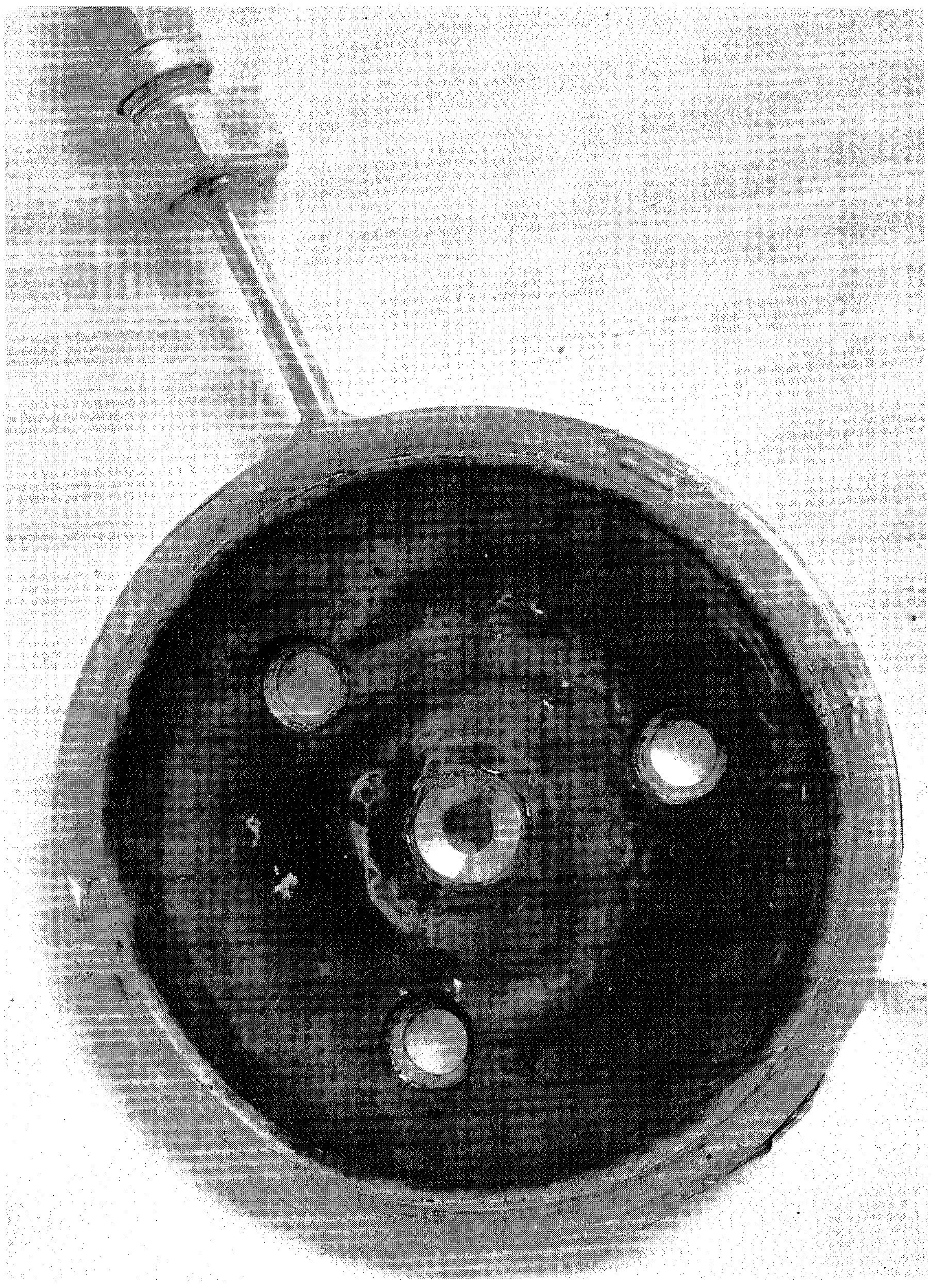

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Figure 27. - 47% Axial Film Cooling Ring After Run 44

Run 46

Run 46 was a long duration run of 130 seconds intended to determine injector and chamber endurance. A POCO heat sink chamber with an L* of 11 inches (28 cm) was used. No PG sleeve was used in this test. The mixture ratio was 5.2 and the new 27% film ring was cleaned after Run 45 and used. Carbon deposition on the chamber near the injector face was not significant and there was some erosion of the POCO graphite in the chamber region near the injector, as shown in Figure 28. One ridge of carbon build-up began in the chamber about 1 inch (2.54 cm) from the injector, and extended through the throat, as shown in Figure 29. In other portions of the throat, erosion had occurred, and the average throat diameter, excluding the carbon ridge, was 0.498 inch (1.27 cm) compared to an original diameter of 0.416 inch (1.06 cm). The chamber pressure had increased in several abrupt steps during the run, as shown in the chamber pressure record in Figure 30. At 130 seconds, the chamber pressure dropped abruptly, and the run was terminated. Post-run inspection revealed melting of several aluminum washers on the chamber attach bolts, indicating that the flange temperature was above 1220°F (933°K) at that time. The carbon deposition on the 27% film cooling ring after Run 46 is shown in Figure 31.

Runs 47 to 52

Engine performance with the short L* (7 inch) (17.8 cm) copper chamber and 27% film cooling was obtained at mixture ratios from 4.2 to 5.44 during Runs 47 to 52. Performance was low, with C* efficiencies from 75% to 81%, as shown in Figure 26. Post-run water flow of the film cooling ring showed that the coolant manifold was leaking badly due to melted failure spots. This indicated that cooling of the ring with only 27% of the methane is inadequate. The low engine performance was probably partly due to the inefficient injection of fuel through the leak areas.

3. 82.5% FLOX/Methane

After Run 52, 82.5% FLOX was loaded into the oxidizer tank and distilled to remove impurities which can cause plugging of small orifices.

Runs 53 to 59

Engine performance using 47% film cooling and a copper chamber L* of 11 inches (28 cm) was determined during Runs 53 to 59. The mixture ratio varied from 4.2 to 5.16. The C* efficiency was found to be about 84% during Runs 53, 54 and 55, with oxidizer and fuel manifold pressures not stabilized. This indicates the possibility of two-phase injection. Subsequent runs showed higher performance, from 88% to 90.5% C* at mixture ratios from 4.84 to 5.16.

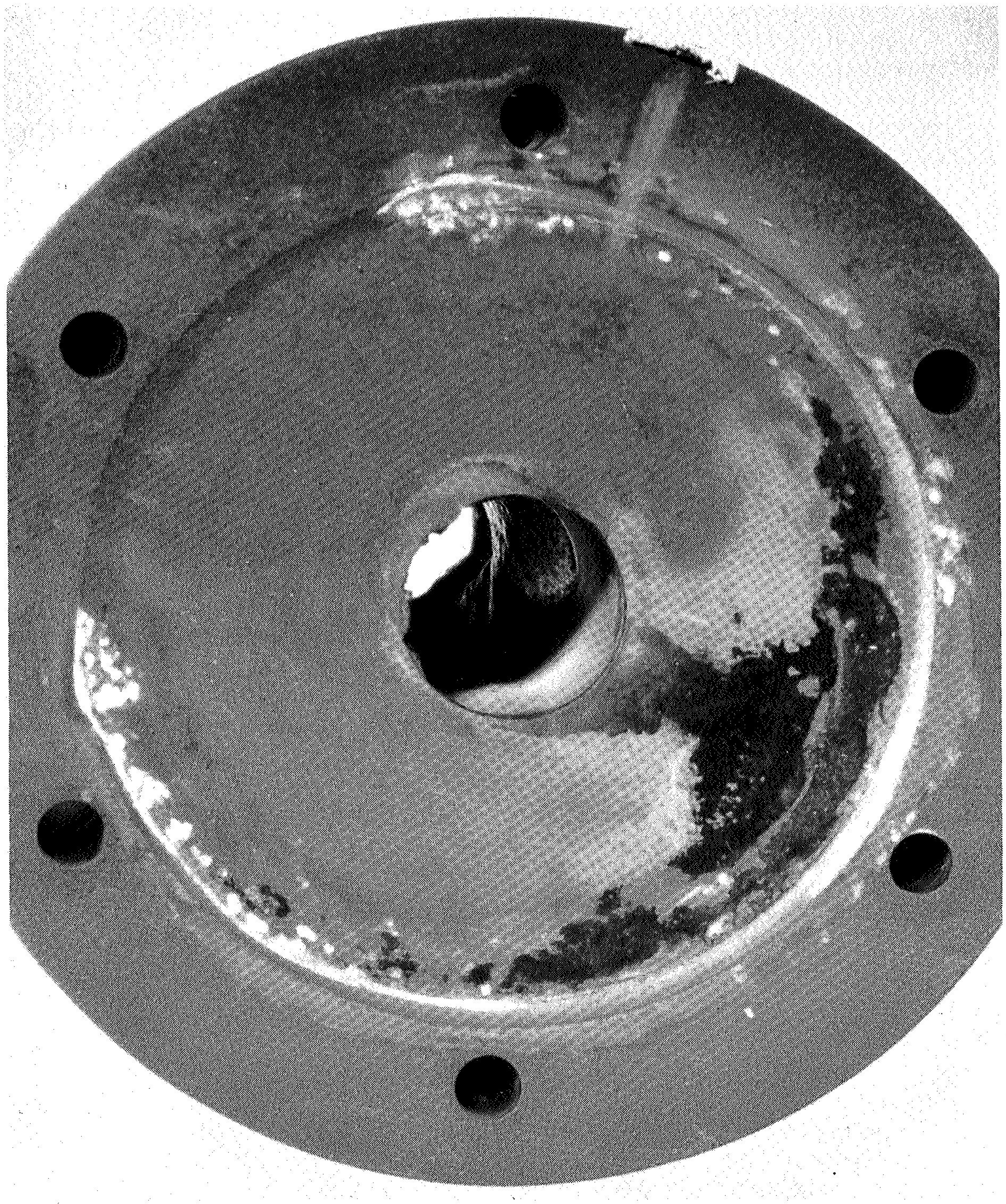

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Figure 28. - POCO Chamber After Run 46

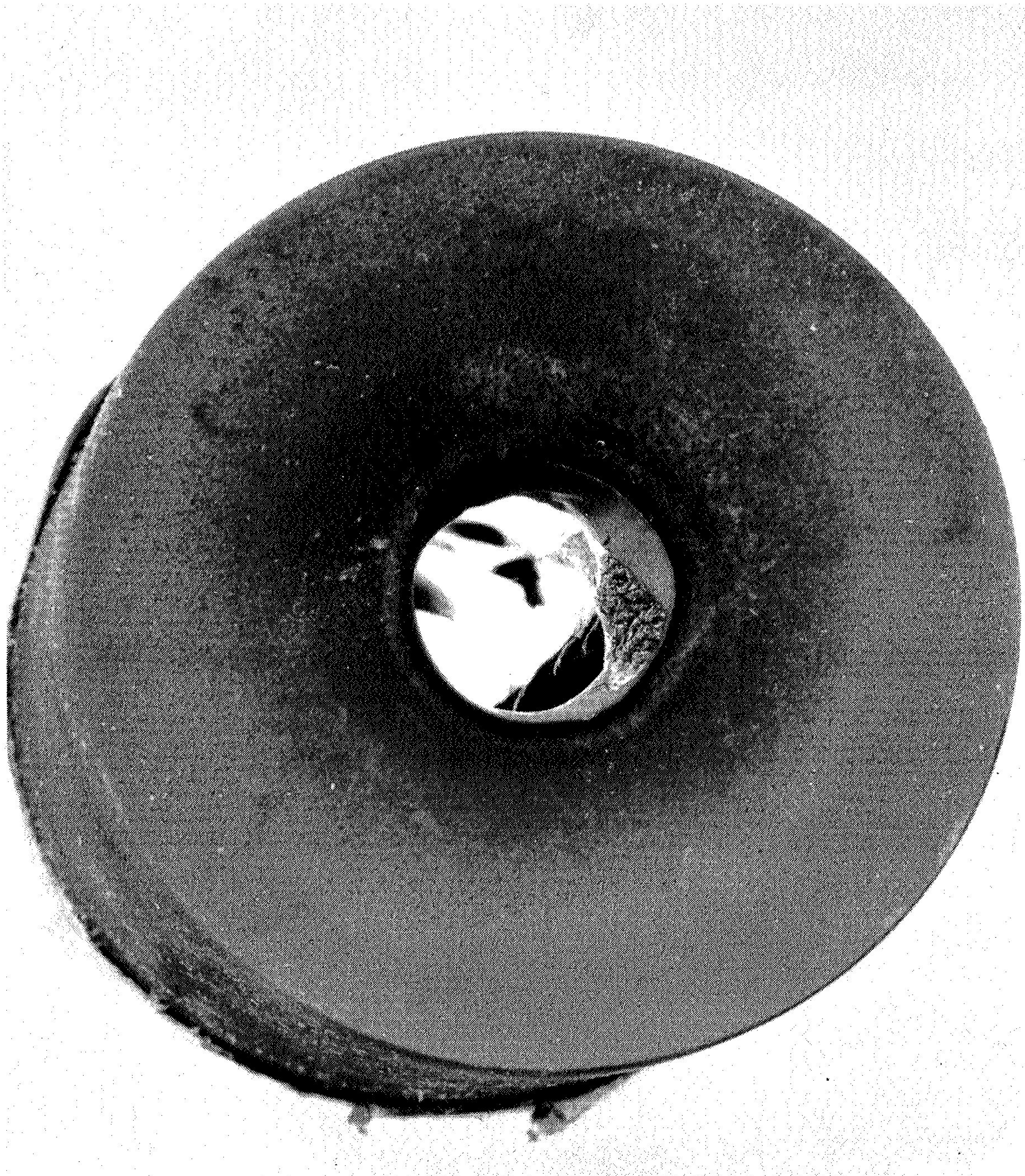

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Figure 29. - POCO Throat After Run 46

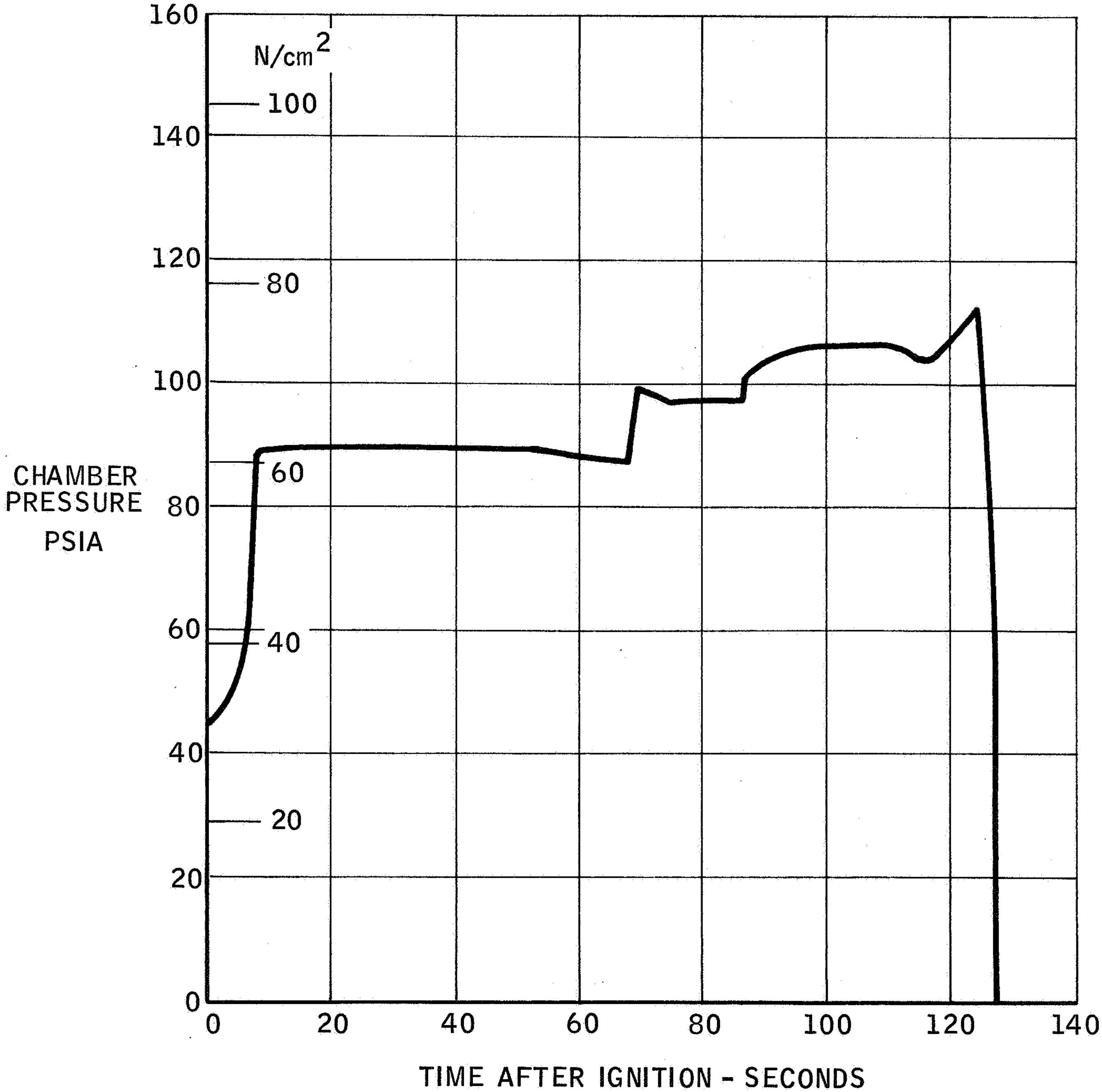

Figure 30. - Chamber Pressure Vs. Time for Run 46
FLOX/Methane

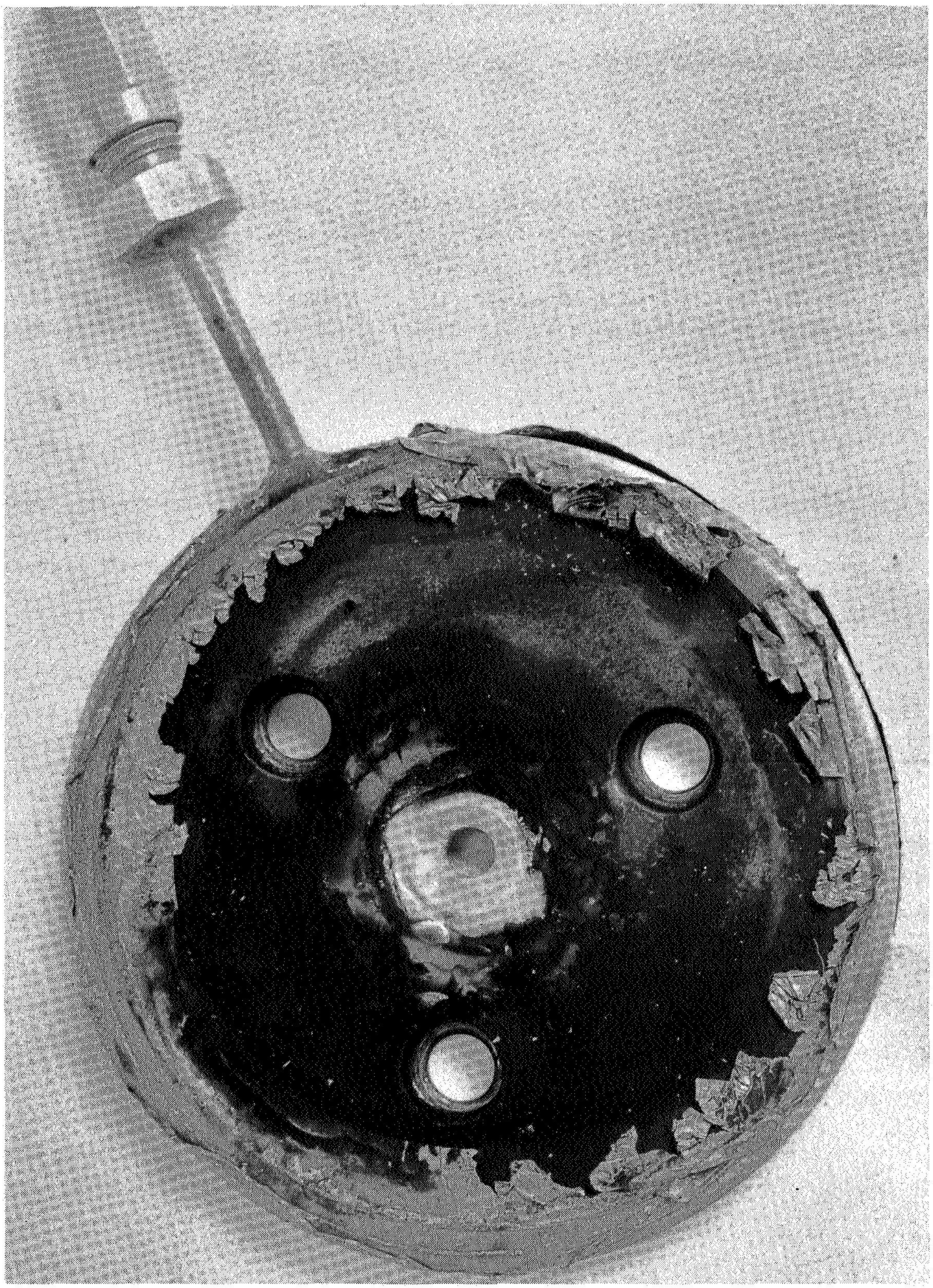

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Figure 31. - 27% Axial Film Cooling Ring After Run 46

The problem of injector conditioning for cryogenic methane is more difficult than for cryogenic propane because of its much lower boiling point. This may explain the low performance with the early runs with methane in the series of test runs 36 to 42 and 53 to 55.

Run 60

A long duration run with a POCO heat sink chamber and PG sleeve was made immediately after Run 59. The film cooling ring was not cleaned before the run but it was determined by passing nitrogen purge through the ring and wetting the surface with "Snoop" fluid that the film cooling holes were flowing despite carbon deposits. The 47% axial film cooling ring (shroud removed) was used. The chamber L* was 11 inches (28 cm). The mixture ratio was 5.16. The chamber failed after 120 seconds. Post-run examination of the chamber pieces indicated that the failure was caused by an axial thermal stress crack in the POCO chamber flange through a bolt hole.

After Run 60, the film cooling ring was completely covered with carbon, but all 24 film cooling jets were probably flowing freely, as a small orifice through the carbon at each film cooling jet was formed for each orifice as shown in Figure 32. Regions of carbon buildup and erosion were found on the PG sleeve, as shown in the photo. The carbon buildup formed a web which attached to the injector end of the PG sleeve as shown in Figure 32. The chamber pressure history is shown in Figure 33 indicating a steadily increasing buildup of chamber pressure after about 30 seconds.

Test firings were completed with Run 60, since it was thought that the results satisfactorily established the characteristics of engine performance, carbon deposition and chamber erosion for the 25 pound thrust liquid FLOX/LPG injector and graphite chambers using either liquid methane or propane as film cooling.

Propellant Conditioning Control

Maintaining control of the thermodynamic state of the propellants at the inlet to the injector has presented a problem area. The desired propellant temperatures for the fuel and oxidizer supply systems are accurately controlled up to the engine propellant valves through the use of LN_2 at carefully controlled pressures and temperatures. The valves and injector are not adequately precooled to prevent partial boiling of the propellants during the initial phases of a run. As the run progresses, the flowing propellants cool the bipropellant valve and injector until saturated liquid flow is established. This situation is more critical for methane than for propane as would be expected due to the lower boiling point of methane. For satisfactory pulse operation with the cryogenic FLOX/LPG propellant combination, extensive heat transfer analysis and a lightweight injector design will be required in order to eliminate two-phase flow.

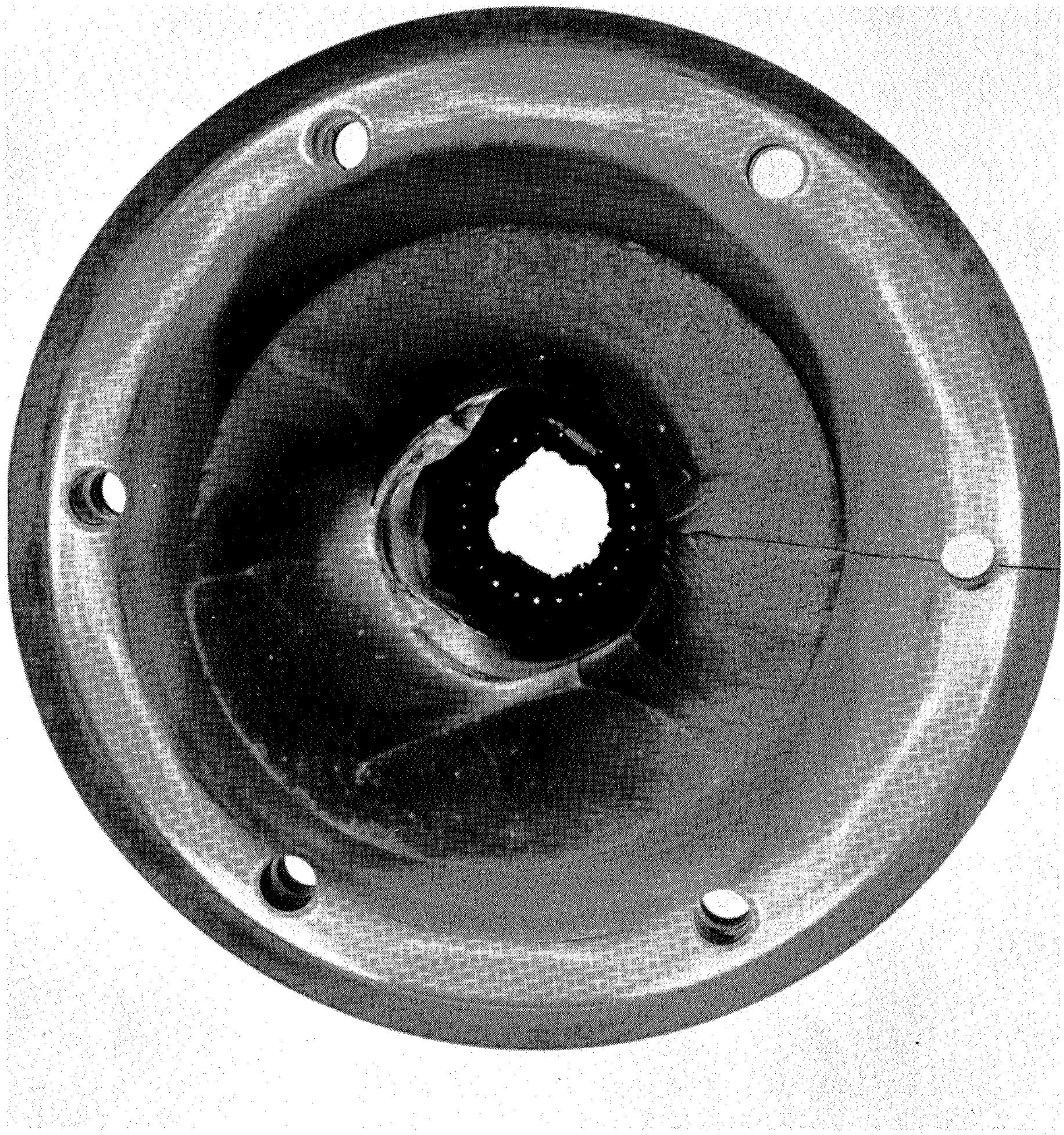

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Figure 32. - Carbon Buildup Adjacent to Film Cooling Ring After Run 60

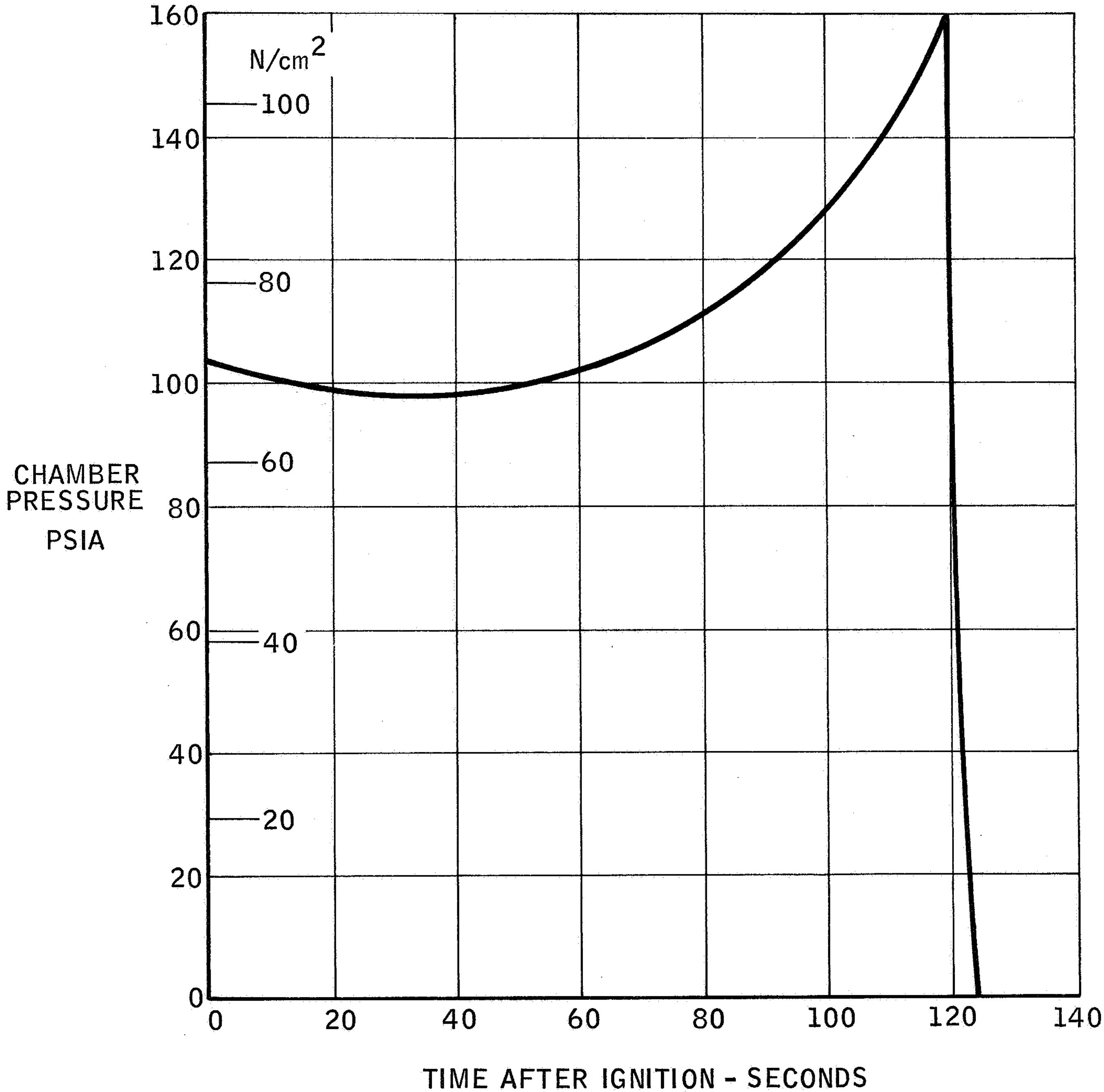

Figure 33. - Chamber Pressure Vs. Time for Run 60
FLOX/Methane

C. Task VI - Graphite Chamber Testing - December 1970

The test results obtained with liquid film cooling (methane or propane) clearly established that long duration runs with graphite chambers were not feasible with that technique of chamber cooling. Therefore, a change in technical approach was used for the last test firings in December 1970, based on the use of gaseous methane film cooling supplied from high pressure methane bottles at room temperature. This technique would be applicable either to gas-gas FLOX/methane or liquid-liquid FLOX/methane if the liquid methane could be vaporized. Methane was used in the December tests because it had produced much less carbon deposition than propane.

The design approach used in the December test series was based on an attempt to eliminate carbon deposition by keeping both the film temperature and the wall temperature below 1400°F (1033°K) the approximate threshold of methane pyrolysis. Furthermore, high purity Instrument Grade methane was used to essentially eliminate impurities such as ethane and propane which are present in the Technical Grade methane used earlier in the program. Both propane and ethane have lower pyrolysis temperatures than methane, and might initiate carbon deposition at lower film or wall temperatures than methane. A comparison of the chemical composition of several grades of methane is given in Table V.

The engine configuration used in the December tests is shown in Figure 11. The new engine components used with gas film cooling are discussed below:

1. Water Cooled Adapter

The water cooled adapter, made of Nickel 200, replaced the film cooling ring used in the previous test firings. The beveled shoulder adjacent to the injector core was cut back 0.030 inch (0.0762 cm) to eliminate the slight erosion experienced in the last configuration. The chamber pressure tap was relocated to run through a drilled hole in the injector flange into an existing tapped hole which opened to a passage through the water cooled adapter. The water cooled adapter was clamped between the injector and the gas cooling adapter.

2. Gas Cooling Adapter

The gas cooling adapter was made of Nickel 200 and injected gaseous methane parallel to the chamber wall. The film cooling slot formed between the chamber ID and the OD of the lip on the water cooled adapter was 0.003 inch (0.0076 cm), controlled to tight tolerances.

TABLE V

COMPOSITION OF GASEOUS METHANE[1]

CONSTITUENT		COMPOSITION - MOLE PERCENT		
		Technical Grade	Chemically Pure	Instrument Grade
Methane	Guaranteed		99.000	99.700
	Typical	97.000	99.360	99.830
Oxygen	Guaranteed	.025	.006	.004
	Typical		.004	.0025
Nitrogen	Guaranteed	.800	.500	.25
	Typical		.350	.16
Carbon Dioxide	Guaranteed	.010	.010	.001
	Typical		.001	.001
Ethane	Guaranteed	2.500	.500	.050
	Typical		.280	.005
Propane	Guaranteed	.600	.030	.003
	Typical		.005	.0005
Water	Guaranteed	.012	.001	.0004
	Typical		.0001	.0001

(1) Ref: Air Products, Inc.

Optimum gaseous film cooling efficiency is obtained by injecting the coolant parallel to the wall at a velocity equal to the freestream velocity. In this case, the best estimate of the freestream velocity is the value of the core velocity of the combustion gase, which is about 270 ft/sec (82.5 m/sec).

The injection velocity of the gaseous methane coolant passing through the 0.003 inch (0.0076 cm) gap was near 270 ft/sec (82.5 m/sec) for 60% cooling at a mixture ratio of 4.5.

3. <u>POCO Chambers</u>

Chambers made of POCO graphite were assembled as shown in the bottom half of Figure 11. The graphite chamber flange was reduced in diameter and attach bolt holes were eliminated. These changes were expected to eliminate the thermal stress failure through a bolt hole which occurred in the testing in April. POCO chambers for chamber lengths of 2.5, 3.0 and 3.5 inches (6.35, 7.62 and 8.9 cm) were fabricated.

The chamber inside diameter was increased to 1.33 inches (3.38 cm) (a contraction ratio of 10:1) for the December tests in order to reduce the heat flux to the chamber.

4. <u>Copper Chamber</u>

A copper chamber with a chamber length of 2.5 inches (6.35 cm) was used with sheathed thermocouples in the flange and throat. Bare thermocouples were also installed in recessed cavities in the flange and throat to measure the film or recovery temperature. Three cylindrical copper sections were also available to increase the copper chamber length to as much as 4.0 inches (10.16 cm).

<u>Test Firings</u>

Test firings were made on December 1-3, 1970. A test summary is given in Table VI.

<u>Runs 61-64</u>

Engine performance for several mixture ratios and amounts of film cooling was determined during short runs with the copper chamber.

Steady-state data were obtained during 20 second firings during Runs 62, 63 and 64 with the chamber cooling reduced for each successive run by using increasing mixture ratios and decreasing amounts of film cooling. The film temperature measurements

TABLE VI

TEST FIRING SUMMARY - TASK VI - DECEMBER 1970

25-Pound-Thrust FLOX/Methane Engine - Gaseous Methane Cooling

Run No.	Date	Chamber	Length In. (cm)	Run Duration Sec.	O/F	C* ft/sec (m/sec)	C* Eff. %	Chamber Pressure psia (N/cm^2)	% Film Cooling	Remarks
61	12/1/70	Copper	2.5 (6.35)	10	← No Data →					
62	12/1/70	Copper	2.5 (6.35)	20	3.54	6090 (1858)	91.0	93.3 (64.2)	77.4	
63	12/1/70	Copper	2.5 (6.35)	20	4.50	5950 (1815)	86.5	90.3 (62.1)	68.0	
64	12/1/70	Copper	2.5 (6.35	20	6.09	5690 (1735)	81.6	89.3 (61.5)	62.5	Carbon Depos.
65	12/2/70	POCO	3.0 (7.62)	120	3.82	Throat Area Uncertain			76.4	Throat Erosion
66	12/3/70	Copper	2.5 (6.35)	30	2.59	6370 (1945)	97.5	128.0 (88.2)	53.0	
67	12/3/70	Copper	2.5 (6.35)	25	3.45	6580 (2010)	98.4	123.0 (84.8)	39.0	Throat Erosion

at 0.62 inch (1.57 cm) from the injection point are in Table VII and indicate that it would not be possible to keep the film below 1400°F (1033°K) throughout the chamber, which was the design objective to avoid thermal decomposition of the methane film. The film temperatures at the throat fluctuated widely in the range of 1900°F to 2500°F (1310°K to 1640°K) and were not considered reliable measurements. However, their average magnitude indicated again the impossibility of maintaining the film temperature below 1400°F (1033°K) even for the optimized film cooling technique utilized.

Run 65

A POCO chamber with a total chamber length of 3.0 (7.62 cm) inches was tested for 120 seconds at approximately the same conditions as had been shown during Run 62 to produce good combustion efficiency (91% C*) with a large amount of film cooling. The chamber pressure varied during the run, with an initial buildup, followed by a sudden decrease at 93 seconds. Another buildup began shortly thereafter, and the run was terminated at 120 seconds.

Both erosion and carbon deposition had occurred in the throat, as shown in Figure 34. Engine performance was not calculated for this run because of the uncertainty regarding throat area.

The inside of the combustion chamber had massive carbon deposition as shown in Figure 35. The deposition began about 0.70 inch (1.78 cm) downstream from the film cooling injection station, which was an improvement over the deposition from liquid film cooling, but not enough of an improvement to permit long duration firings.

Runs 66 and 67

The copper chamber was tested with reduced amounts of film cooling to collect more film cooling and performance data. The engine performance was very good (about 98% C* efficiency) for film cooling percentages of 53% and 39%. The test conditions of Run 67 were chosen to use a film cooling flow rate of 0.0075 lb/sec (0.0034 kg/sec) to achieve optimum film cooling efficiency with the 0.003 inch (0.00762 cm) film injection gap. It was predicted that with 40% film cooling, (0.0075 lb/sec) (0.0034 kg/sec) the actual film temperature at the throat would be the same as with the use of twice as much coolant (0.015 lb/sec) (0.0068 kg/sec), the nominal condition chosen for Run 66.

TABLE VII

TEMPERATURE MEASUREMENTS - TASK VI - DECEMBER TESTS

Run No.	Time Sec.	Gaseous Film Temperature 0.62 in. from Injection Slot		Chamber Temperature Flange		Chamber Temperature Throat	
		°F	°K	°F	°K	°F	°K
62	20	1335	997	205	370	435	497
63	20	1440	1056	225	381	450	505
64	20	1620	1156	282	412	600	590
66	30	1507	1092	465	514	975	796
67	25	T.C. Failure		450	506	845	725

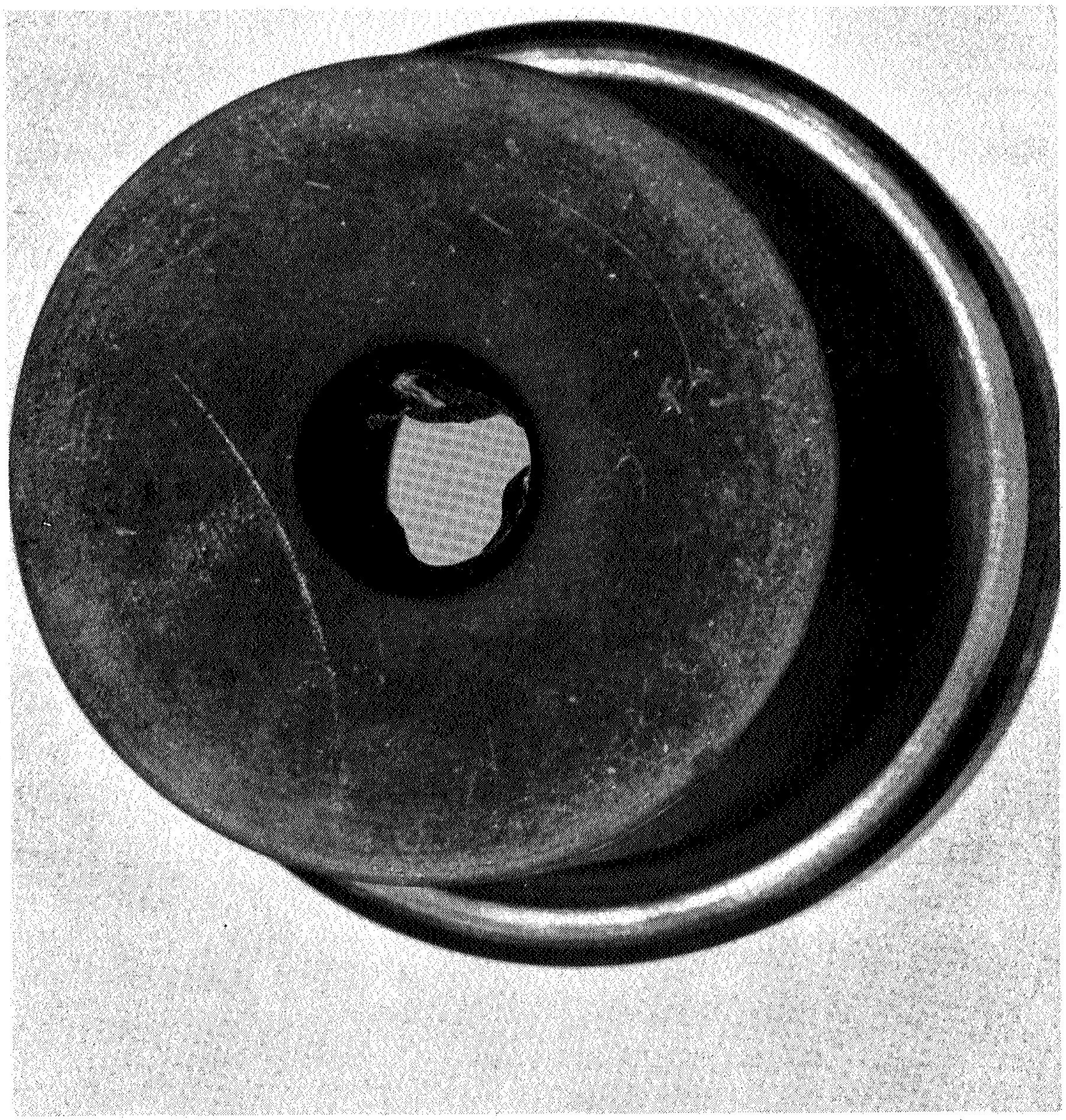

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Figure 34. - POCO Throat After 120 Second Firing with Gaseous Methane Film Cooling (Run 65)

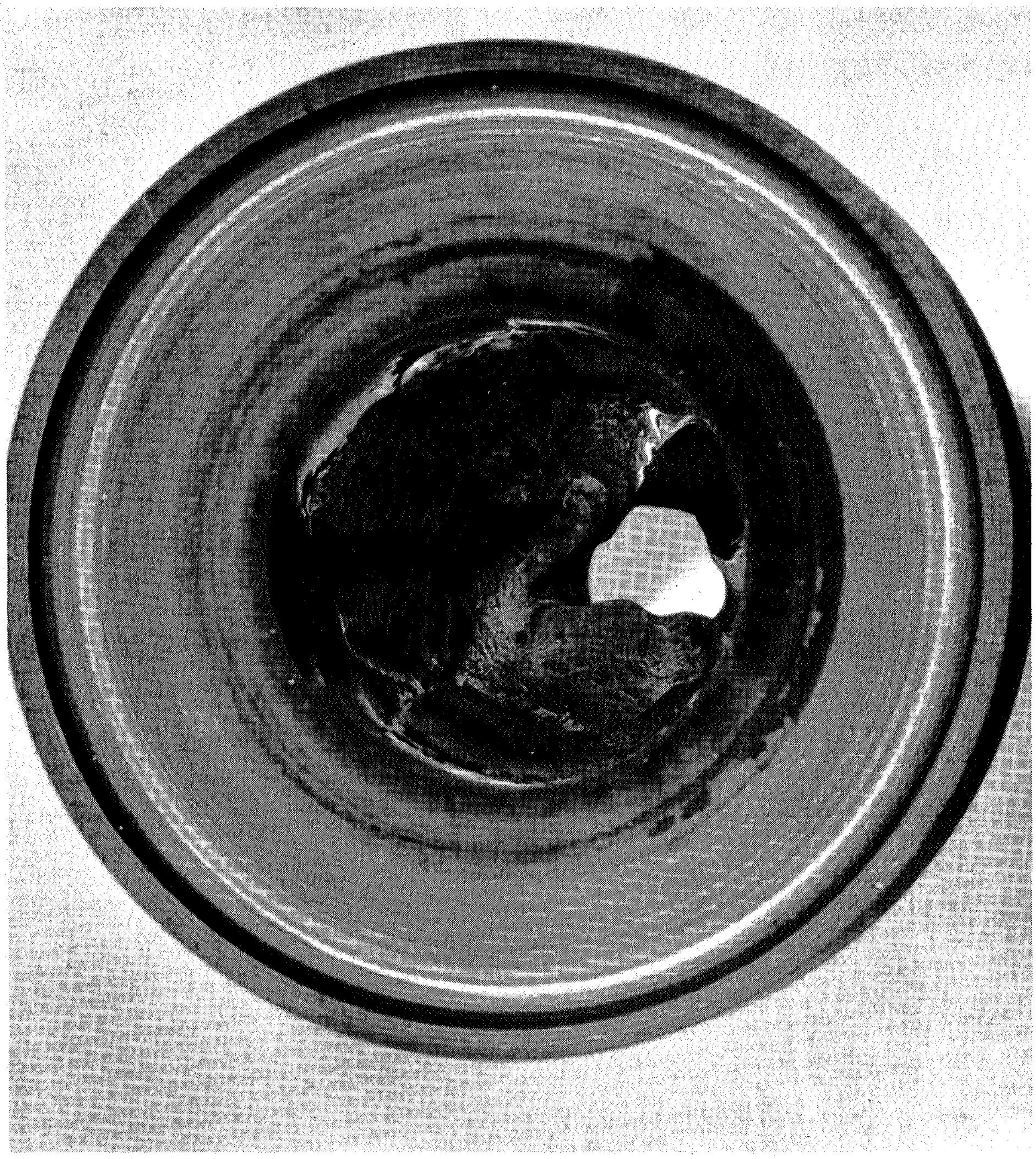

Figure 35. - POCO Chamber After 120 Second Firing with Gaseous Methane Film Cooling (Run 65)

This relationship was substantiated to some extent by the measured wall temperatures at the throat (Table VII) which were approximately the same for Runs 66 and 67, remembering that Run 67 was 5 seconds shorter than Run 66. The wall temperatures were measured by sheathed thermocouples bottomed in holes 1/4 inch from the hot surface. However, the throat of the copper chamber was overheated during Run 67 in a location between wall thermocouples, causing throat enlargement. Post-run examination of the copper chamber showed some carbon deposition at the beginning of the contraction section.

Conclusions

The results of the December tests lead to the conclusion that neither the use of instrument grade methane or optimized gaseous methane film cooling were able to eliminate carbon deposition in graphite or copper thrust chambers or to accomplish sufficient cooling for long duration capability.

SECTION VII
CONCLUSIONS

The results of this program lead to the following conclusions:

1. Carbon was deposited on the chamber walls and throat for run durations above approximately 20 seconds, regardless of the mixture ratio, amount of film coolant or composition of methane or propane coolant.

2. Carbon deposition is less using methane than when using propane for film cooling.

3. Hydrocarbon film cooling in the configurations tested is not adequate to permit long duration firings of a 25-pound (111.2 newton) thrust engine at a chamber pressure of 100 psia (68.9 N/cm^2) because of the limited cooling capacity of methane or propane at mixture ratios of interest (4 to 5.75), and because of carbon buildup in the chamber and throat.

SECTION VIII
REFERENCES

1. Marquardt Report No. 6147, "Space Storable Thruster Investigation", NASA CR-72526, Contract NAS 3-11215, 10 June 1969.

2. Marquardt Report S-989, "Refractory Composite Materials for Spacecraft Thrust Chambers", Final Report, Contract NAS 7-555, Mod. 3 and 4, 7 May 1971

APPENDIX A

SYMBOLS

SYMBOL	DEFINITION
C*	Characteristic Length
D_f	Fuel Orifice Diameter
D_o	Oxidizer Orifice Diameter
E_m	Mixing Factor
L*	Characteristic Length
P_c	Chamber Pressure
O/F	Mixture Ratio
$\dot{W}_f$	Fuel Flow Rate
$\dot{W}_o$	Oxidizer Flow Rate
α	Injector Element Impingement Angle

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APPENDIX B

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